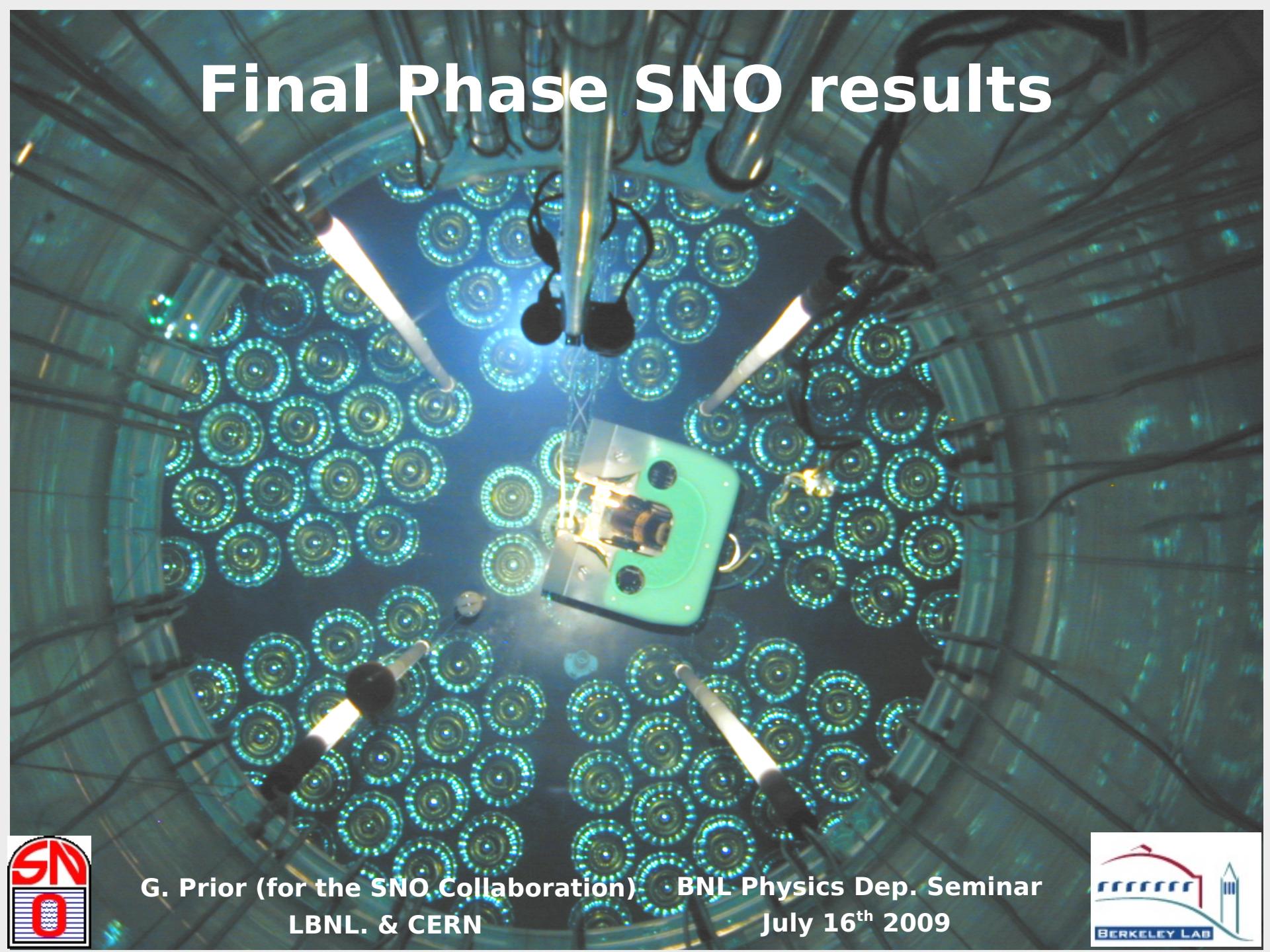


# Final Phase SNO results



G. Prior (for the SNO Collaboration)   BNL Physics Dep. Seminar  
LBNL. & CERN   July 16<sup>th</sup> 2009



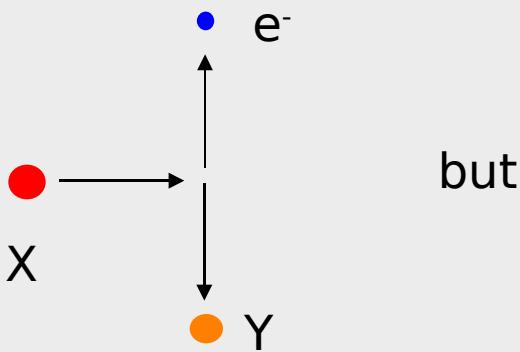
# Roadmap

- A brief history of the neutrino
- Solar neutrinos and pioneers experiments
- The Solar Neutrino Problem
- Neutrino masses and oscillations
- The Sudbury Neutrino Observatory
- Results from the third phase

# A brief history of the neutrino (1/)

- **1930's:  $\beta^-$  was thought to be  $X \rightarrow Y + e^-$**

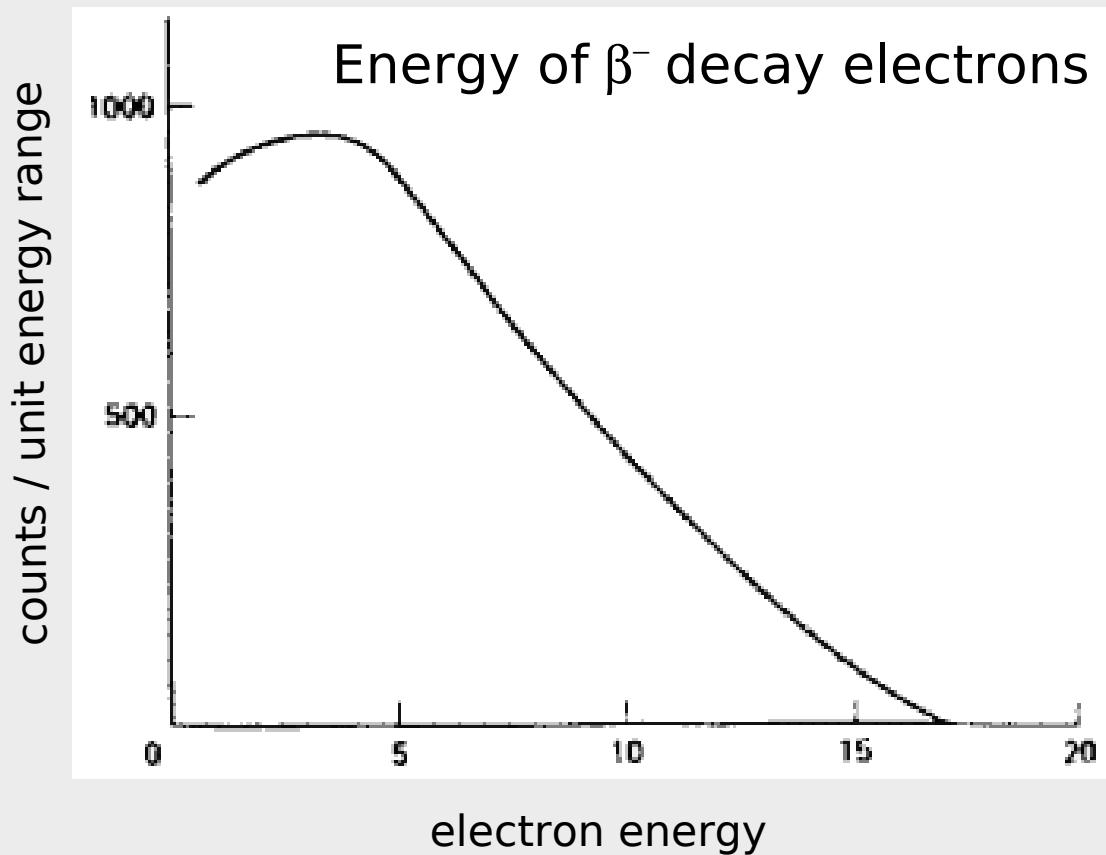
Two body decay: the  $e^-$  energy should come into discrete quantity.



but

W. Pauli: "possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons..."

N. Bohr: "I should say that we have no argument, either empirical or theoretical for upholding the energy principle in case of beta-ray disintegration"



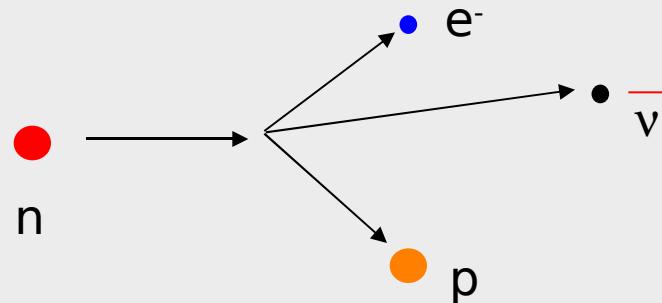
# A brief history of the neutrino (2/)

- In 1932 Chadwick discovers the neutron.

Problem: two heavy to satisfy Pauli's explanation of energy conservation in  $\beta^-$  decay.

- In 1934 Fermi publishes his theory of  $\beta^-$  decay .

Assumes the existence of Pauli's light neutral particle and names it "neutrino".



- In 1956 direct detection of the (anti)-neutrino.

Reines & Cowan's experiment at Savannah River nuclear reactor (S. Carolina):

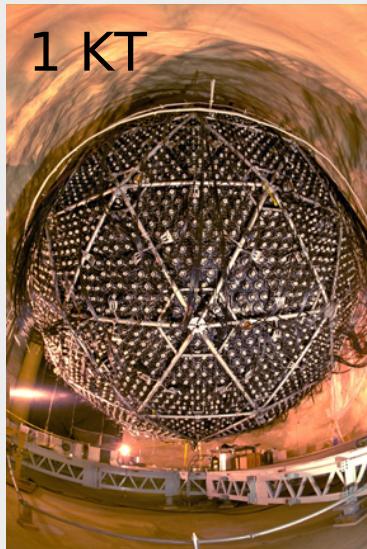


# Neutrinos & their detection

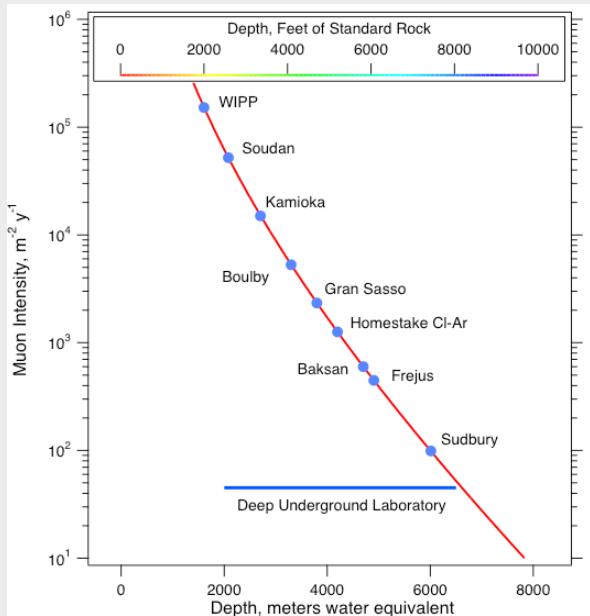
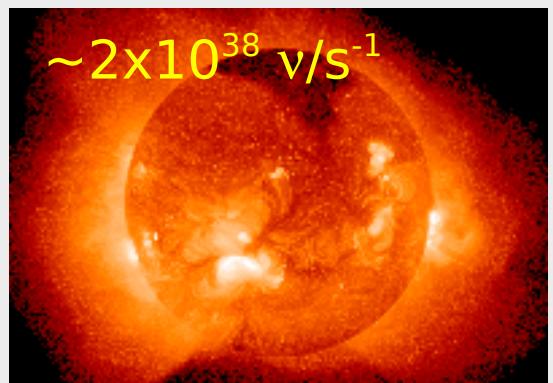
## Standard Model

u up	c charm	t top
d down	s strange	b bottom
$\nu_e$	$\nu_\mu$	$\nu_\tau$
e	$\mu$	$\tau$

Three flavors.  
No charge nor mass.  
Interact only via the  
weak force.



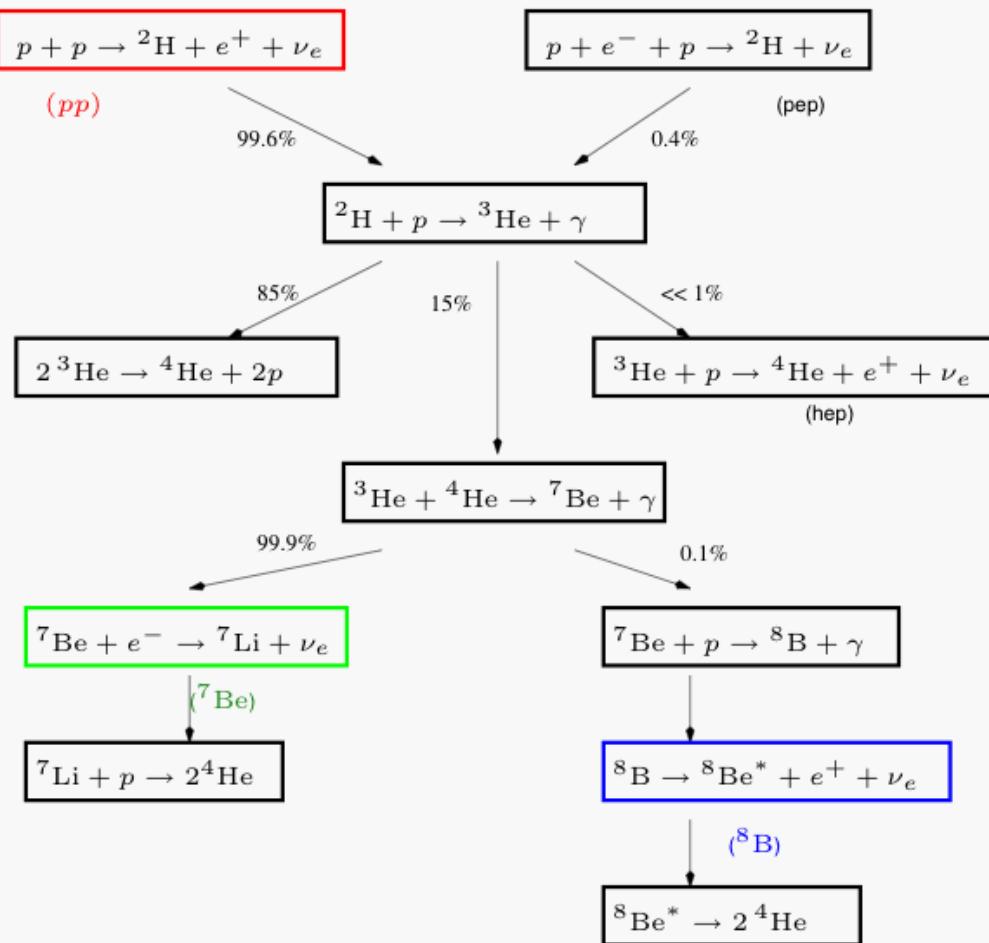
Big detectors  
& powerful sources



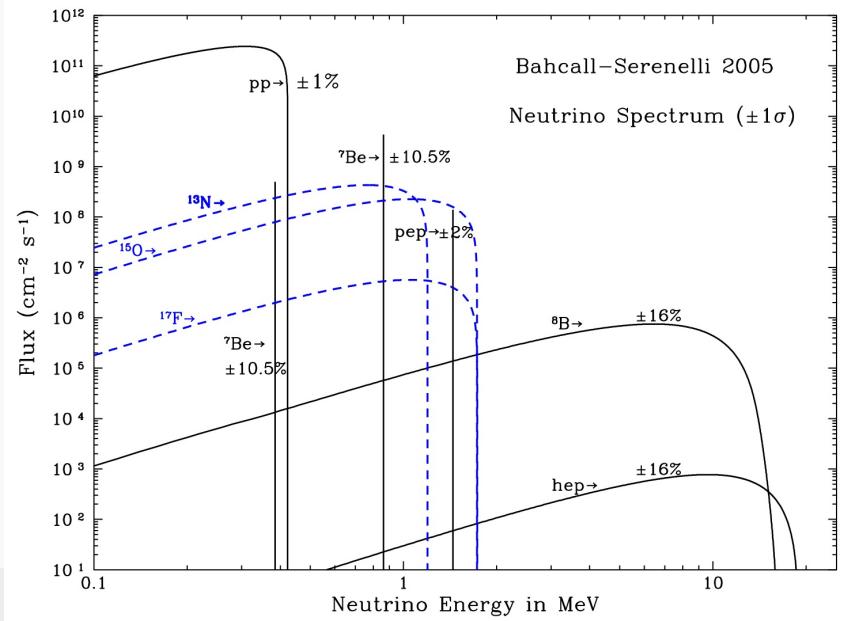
Going deep  
underground

# Solar neutrinos

The pp chain reaction:



**Standard Solar Model (SSM):**  
Detailed solar model calculations give prediction on the solar neutrino flux on Earth.



# Pioneer experiments (1/)

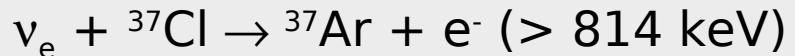
1963, Barbeton



The Chlorine radiochemical experiments:

First attempt by Ray Davis in Barbeton mine (Ohio, 2300 ft depth): could only obtain an upper limit due to the cosmic-ray muon background.

Second attempt in Homestake (South-Dakota, 4850 ft depth) using the reaction:



The  ${}^{37}\text{Ar}$  produced by neutrino interactions was then extracted by purging the tank with helium collecting the He and Ar.

With a 35-day half-life the  ${}^{37}\text{Ar}$  could then be counted.

This experiment took data for over 30 years. Observed solar neutrino rate was  $2.56 \pm 0.16 \text{ (stat.)} \pm 0.15 \text{ (sys.) SNU}$  compared to the predicted rate of  $7.7 {}^{+1.2}_{-1.0} \text{ SNU}$ .

1 SNU (Solar Neutrino Unit) =  $10^{-36} \text{ s}^{-1}$  per target atom.

Tank of cleaning fluid as target.



Ray Davis testing the water

# Pioneer experiments (2/)

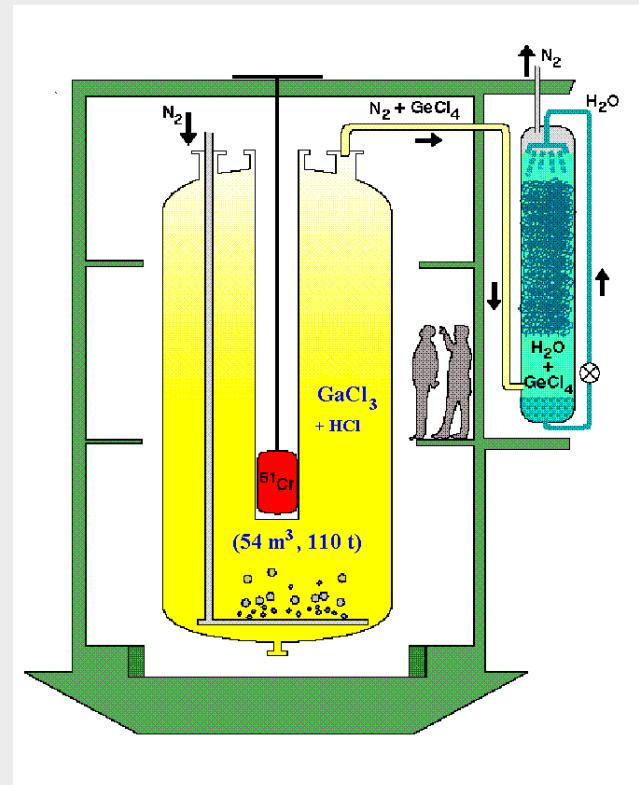
## The Gallium radiochemical experiments:

Another reaction which has been used to study solar neutrinos is:



SAGE experiment which was located in the Baksan Neutrino Observatory (Russia) used Gallium metal and observed a neutrino rate of  $67.2 {}^{+7.2}_{-7.0}$  (stat.)  ${}^{+3.5}_{-3.0}$  (sys.) SNU while the predicted rate for gallium is 129 SNU.

GALLEX and GNO experiments located in Gran-Sasso Laboratory (Italy) have used a gallium chloride solution and observed a rate of  $74.1 {}^{+6.7}_{-6.8}$  SNU.

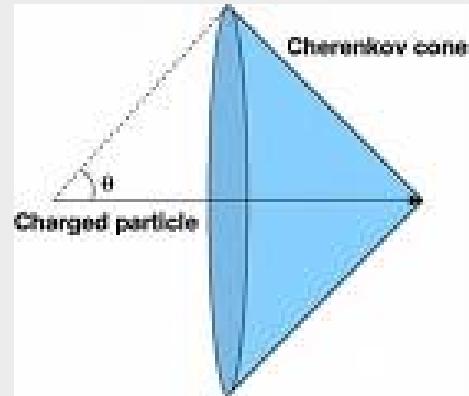


The GALLEX detector

# Pioneer experiments (3/)

## Kamiokande and Super-Kamiokande (Japan):

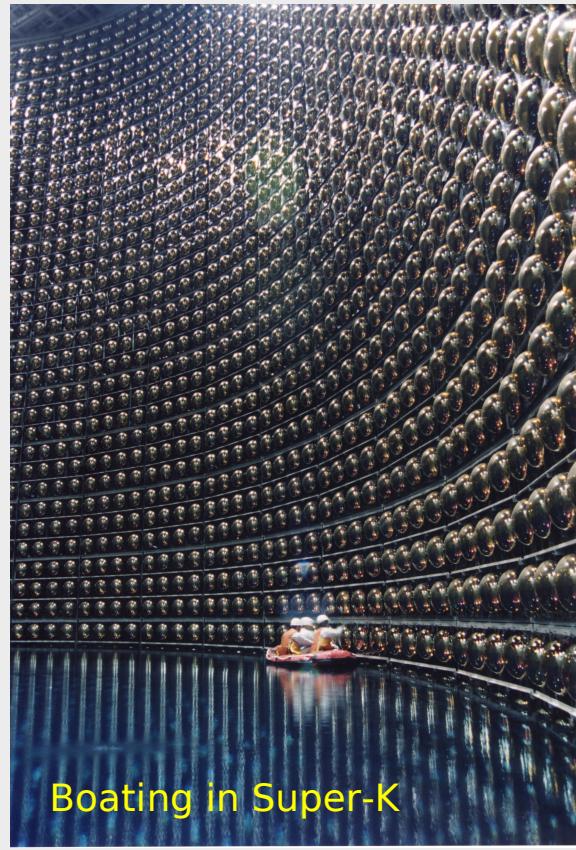
Both used water as target for neutrino interaction:



Scattered electrons are detected by the Cherenkov light they produce.

Kamiokande experiment measured a  $\nu$  flux that was  $0.492^{+0.033}_{-0.034}$  (stat.)  $\pm 0.058$  (sys.) of the expected solar neutrino signal.

Super-Kamiokande has reported detecting  $0.465^{+0.015}_{-0.013}$  (stat.)  $\pm 0.058$  (sys.) of the expected signal with 1496 days of data.



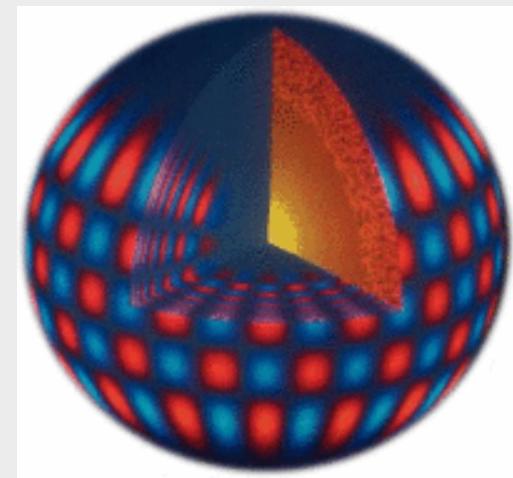
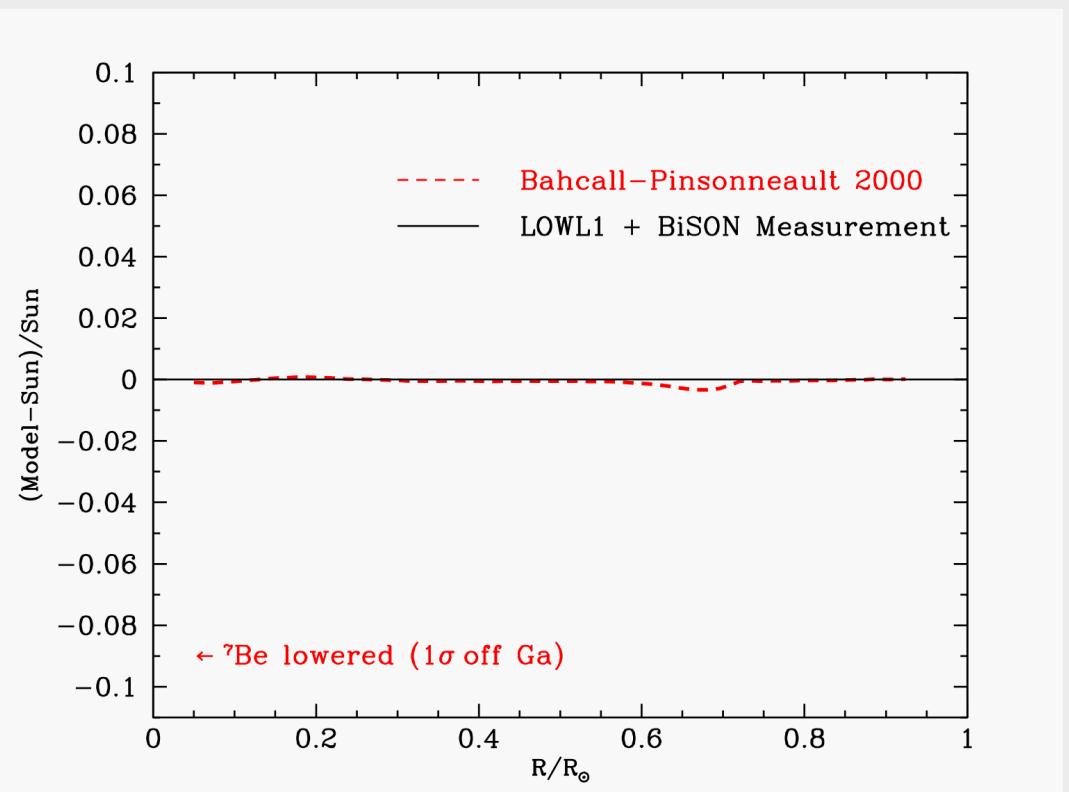
Boating in Super-K

# The Solar neutrino problem

Significant deficit of neutrinos:

- solar model flawed ?
- understanding of neutrinos incomplete ?

Helioseismology measurements agree with the SSM:



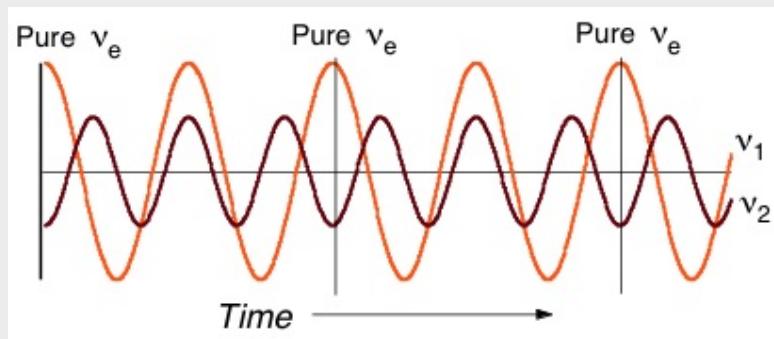
So, what if the neutrinos can change flavors ?

# Neutrino masses and oscillations

Flavor eigenstates are a mixture of mass eigenstates:



From the equation of evolution:



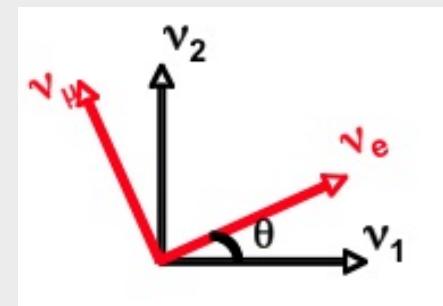
Oscillation probability:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{12}) \cdot \sin^2(1.27 \Delta m_{12}^2 L/E)$$

From mass to flavor:

$$\nu_e = \cos\theta_{12} \cdot \nu_1 + \sin\theta_{12} \cdot \nu_2$$

$$\nu_\mu = -\sin\theta_{12} \cdot \nu_1 + \cos\theta_{12} \cdot \nu_2$$



$$\Delta m_{12}^2 = m_1^2 - m_2^2$$

# The Sudbury Neutrino Observatory

6000 m.w.e. overburden

1000 tons D<sub>2</sub>O

12 m Diameter Acrylic Vessel

1700 tons Inner Shield H<sub>2</sub>O

Support Structure 9500  
PMTs, 60% coverage

5300 tons Outer Shield H<sub>2</sub>O

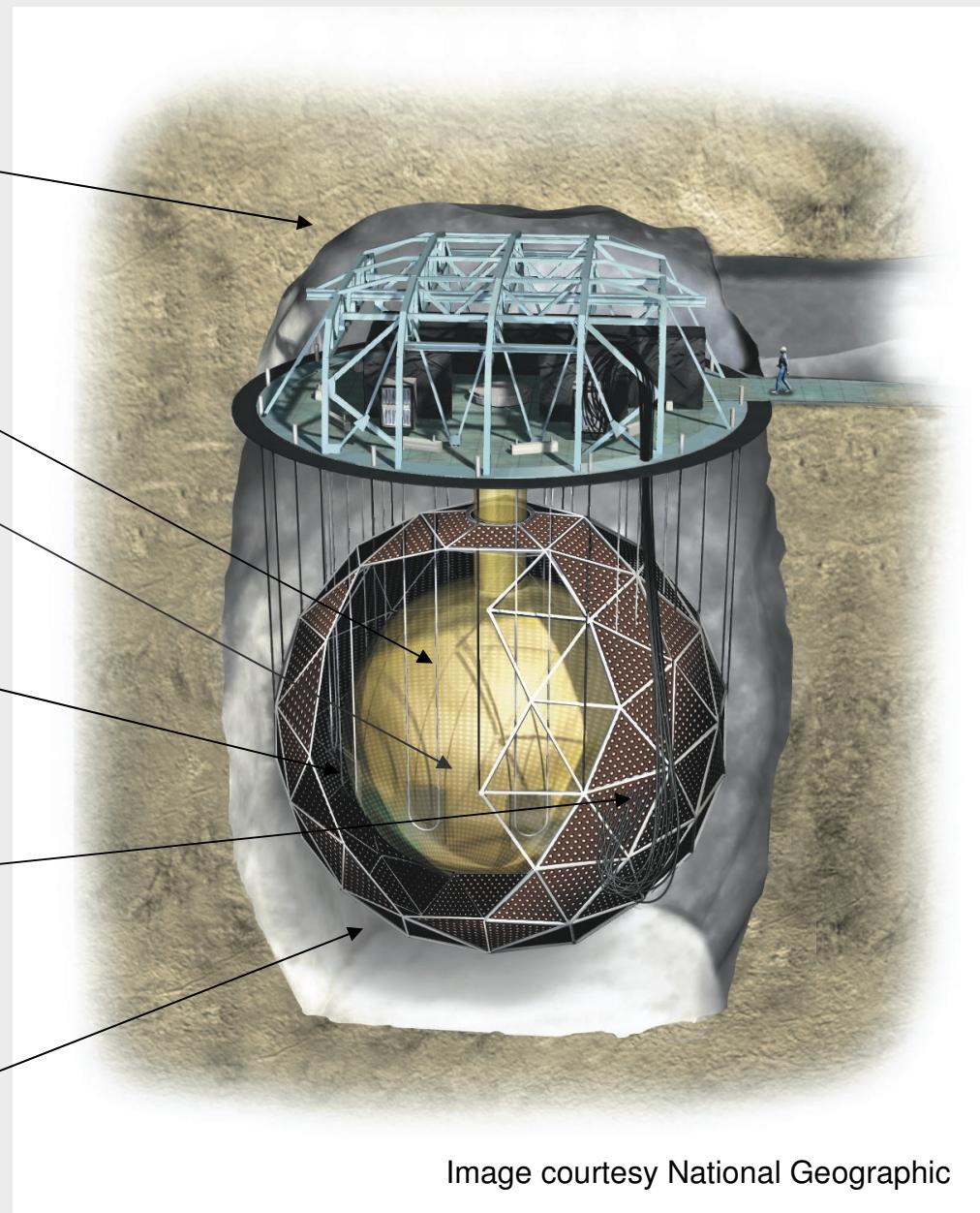
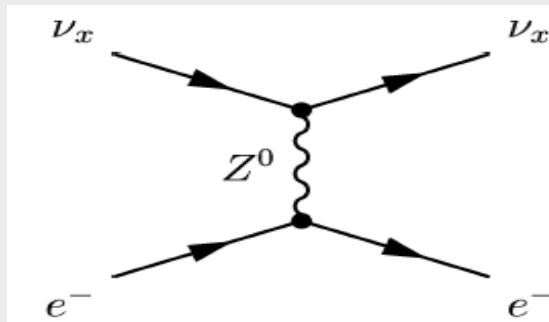


Image courtesy National Geographic

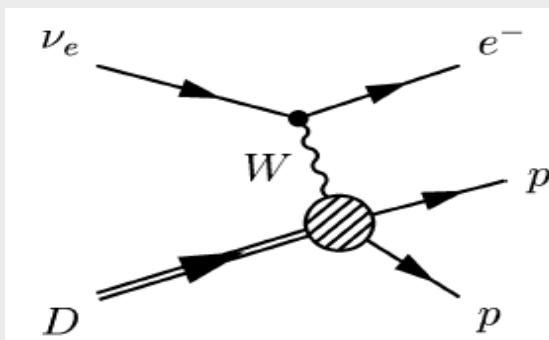
# SNO interactions (from ${}^8\text{B}$ neutrinos)

## Elastic-scattering (ES):



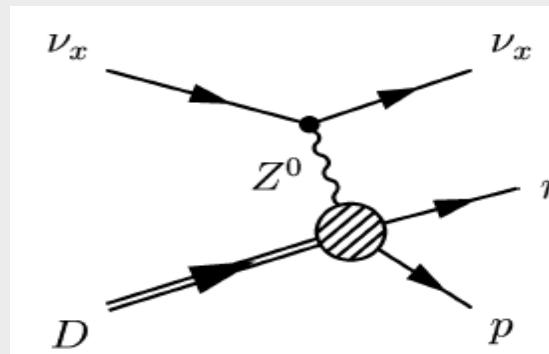
$\nu_e$  mainly  
directional  
sensitivity

## Charged-currents (CC):



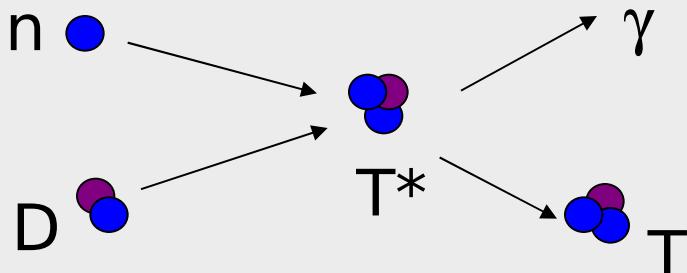
$\nu_e$  only  
 $E_e$  correlated  
with  $E_\nu$

## Neutral-currents (NC):



All flavors  
equally  
Total  $\nu$  flux

# Neutron capture techniques

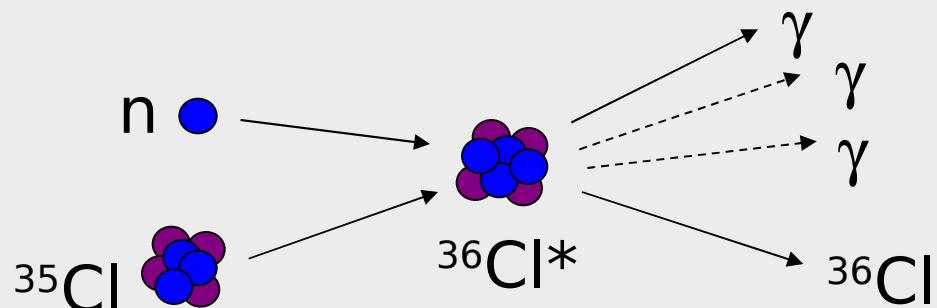


## $D_2O$ Phase:

$$\sigma = 0.0005 \text{ b}$$

$$\varepsilon = 14\%$$

Energy threshold close to background noise (6.25 MeV)

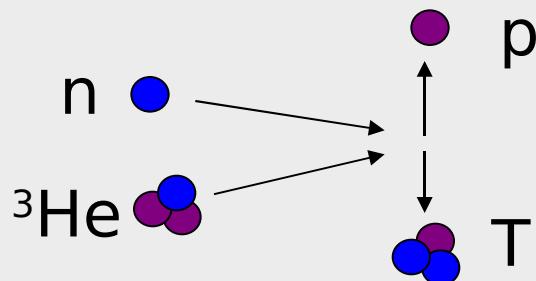


## Salt Phase (2 tons NaCl):

$$\sigma = 44 \text{ b}$$

$$\varepsilon = 41\%$$

Higher energy threshold (8.6 MeV)



## NCD Phase:

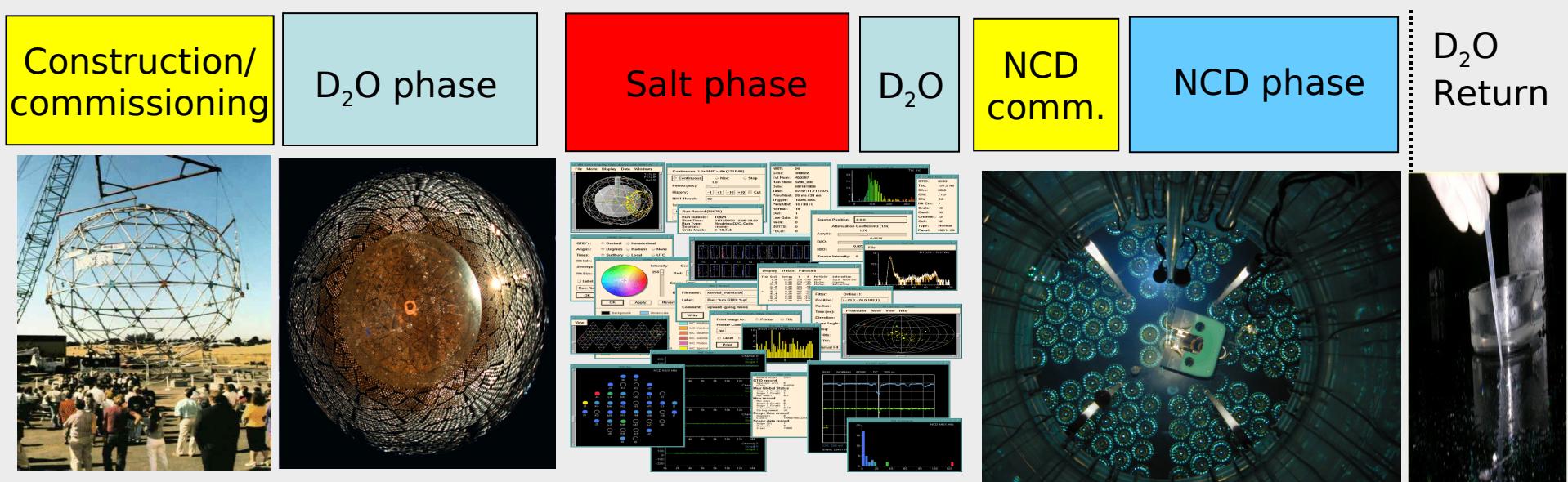
$$\sigma = 5330 \text{ b}$$

$$\varepsilon = 21\%$$

New detectors ( $E=0.76 \text{ MeV}$ )

# SNO Timeline

1998      1999      2000      2001      2002      2003      2004      2005      2006



Super-Kamiokande



Cl



GNO



SAGE



Borexino



KamLAND



KamLAND Solar ↓



# Salt phase results

**Fluxes and ratios ( $10^{-6} \text{ cm}^{-2}\text{s}^{-1}$ ):**

$$\Phi_{\text{CC}} = 1.68 \pm 0.06 \text{ (stat.)} {}^{+0.08}_{-0.09} \text{ (syst.)}$$

$$\frac{\phi_{\text{CC}}}{\phi_{\text{NC}}} = 0.34 \pm 0.023 \text{ (stat.)} {}^{+0.029}_{-0.031} \text{ (syst.)}$$

$$\Phi_{\text{NC}} = 4.94 \pm 0.21 \text{ (stat.)} {}^{+0.38}_{-0.34} \text{ (syst.)}$$

$$\Phi_{\text{ES}} = 2.35 \pm 0.22 \text{ (stat.)} \pm 0.15 \text{ (syst.)}$$

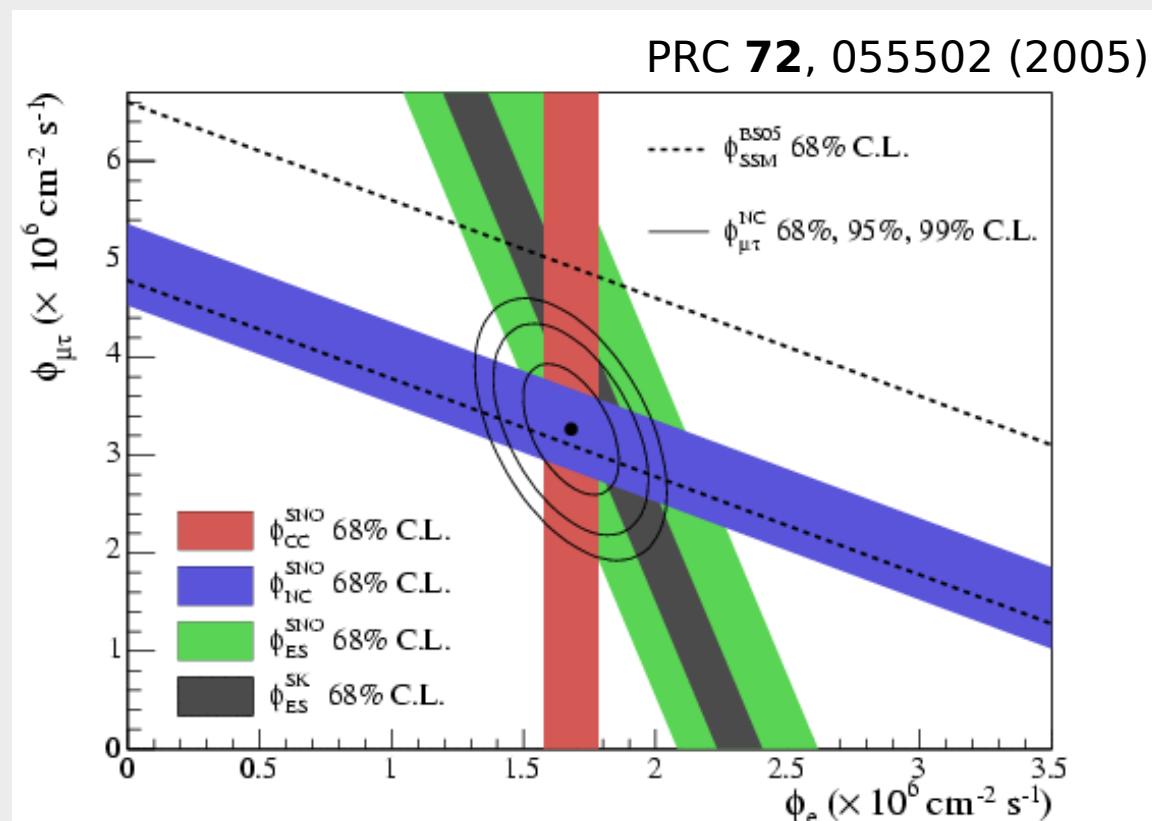
$$(\Phi_{\text{CC}}/\Phi_{\text{NC}} \sim \sin^2 \theta_{12})$$

**Mass:**

$$\Delta m^2 = 0.8 {}^{+0.6}_{-0.4} 10^{-5} \text{ eV}^2$$

**Mixing angle:**

$$\theta_{12} = 33.9 {}^{+2.4}_{-2.2} \text{ degrees}$$



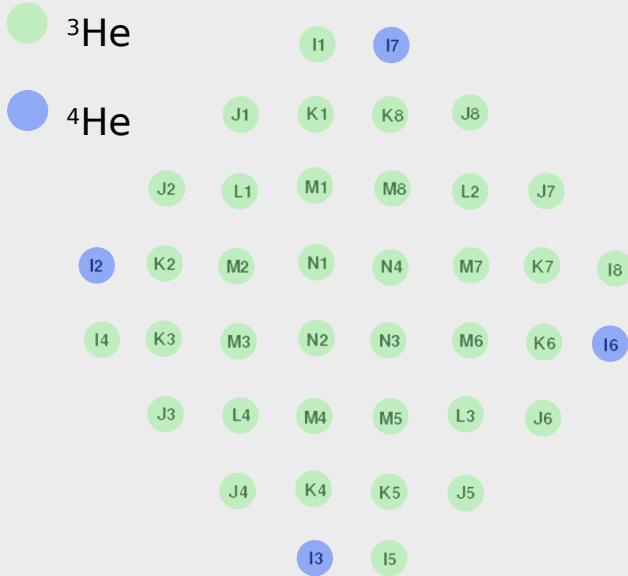
# Neutral Current Detectors (NCD)

## Why:

- Different systematics compared to previous phases
  - Better CC flux measurement
- Correlation between CC and NC signals reduced

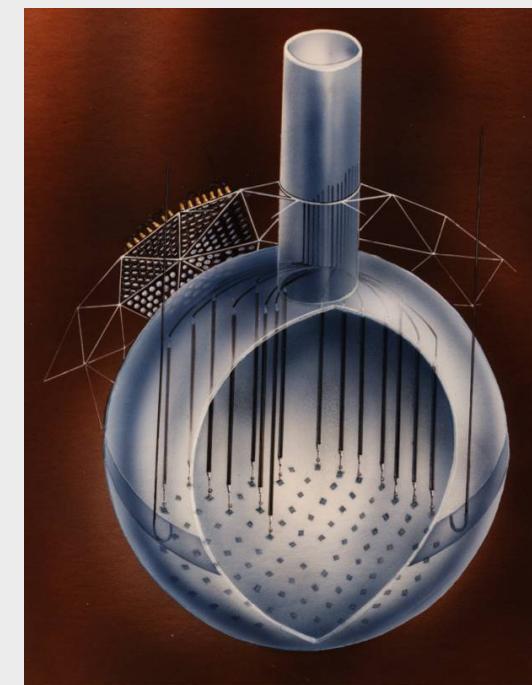
## Challenges:

- Low signal rate:  $\sim 1000$  neutrons/year detected
- Ultra-low background materials needed
- Some light loss ( $\sim 10\%$ ) due to array

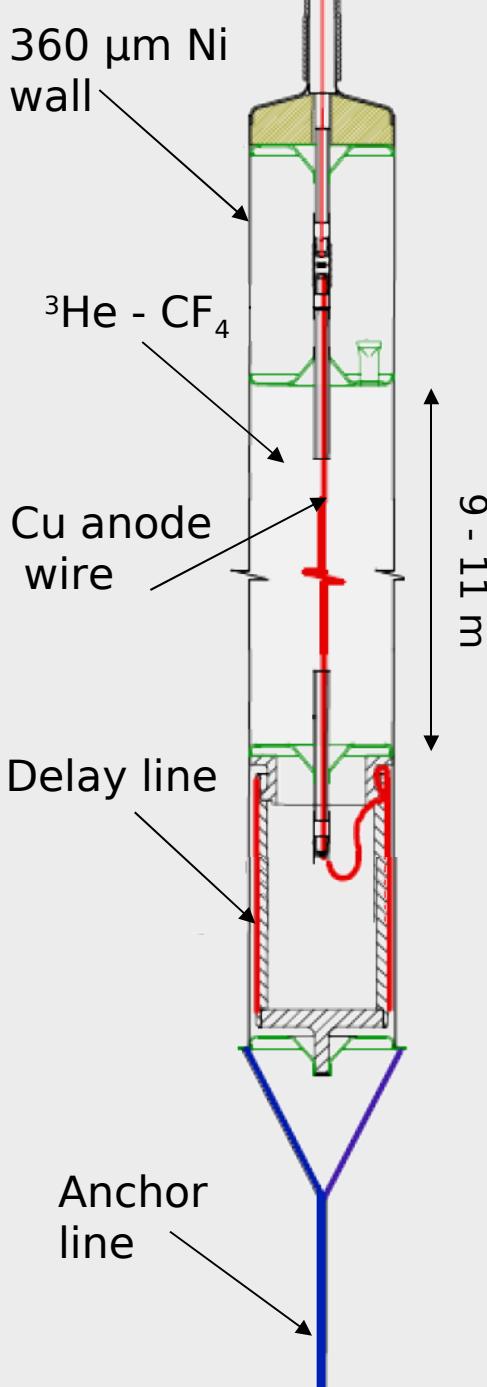


36  $^3\text{He}$  strings and 4  $^4\text{He}$  strings deployed  
on a 1x1 m grid.

Total length 398 m.



# NCD string



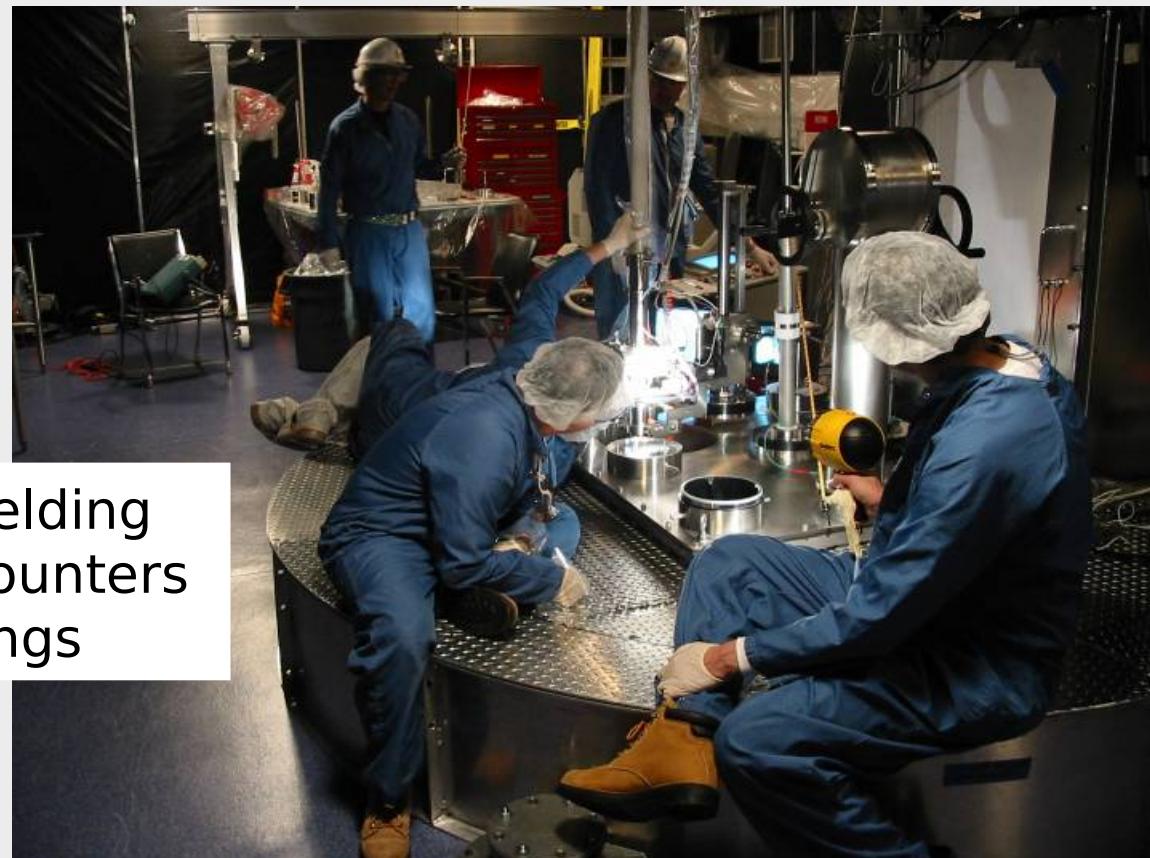
High purity CVD nickel:

$$\text{gTh/gNCD} = 3.43^{+1.49}_{-2.11} \times 10^{-12}$$

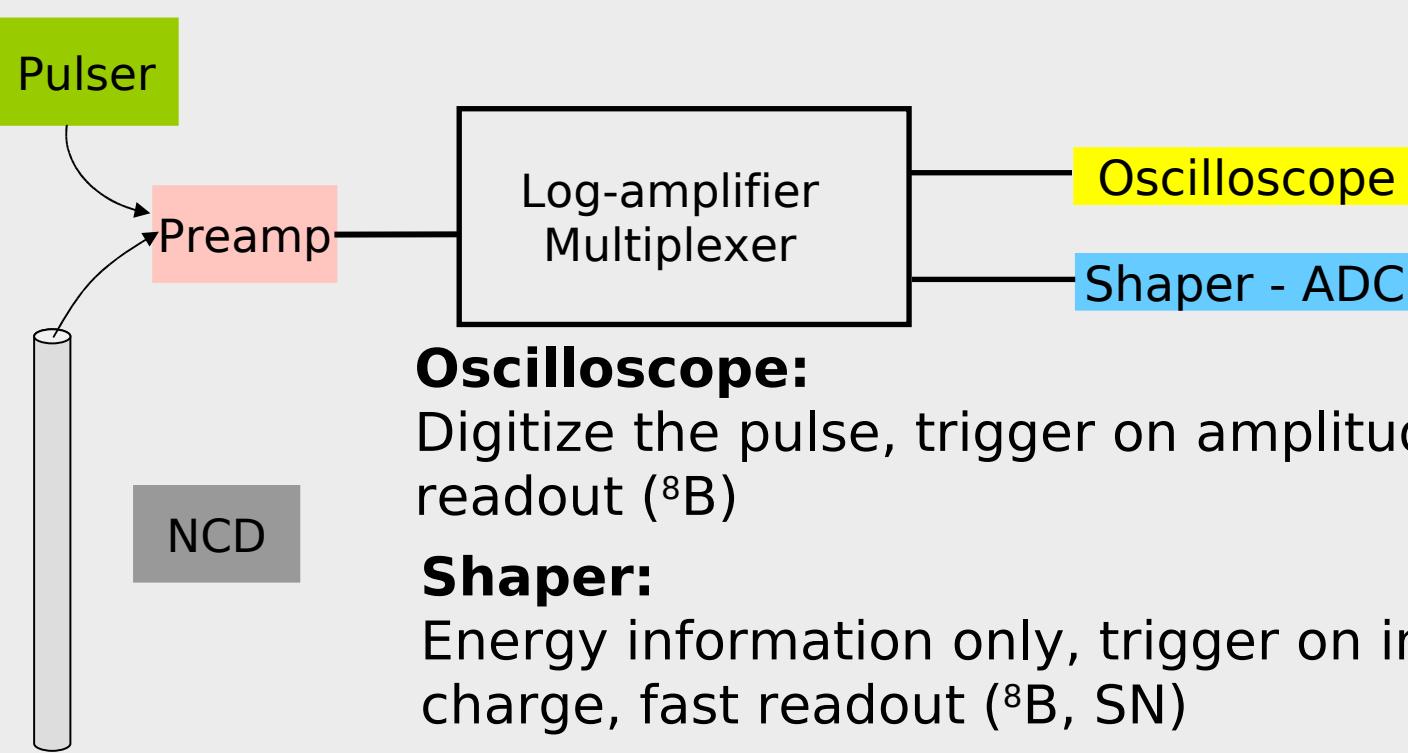
$$\text{gU/gNCD} = 1.81^{+0.80}_{-1.12} \times 10^{-12}$$

(100 times purer  
than previous  
counters)

Laser welding  
of the counters  
into strings



# NCD electronics and signal

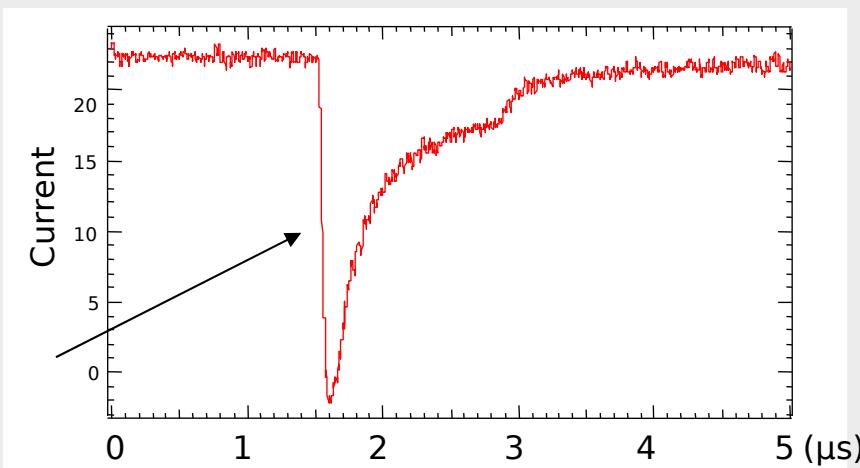
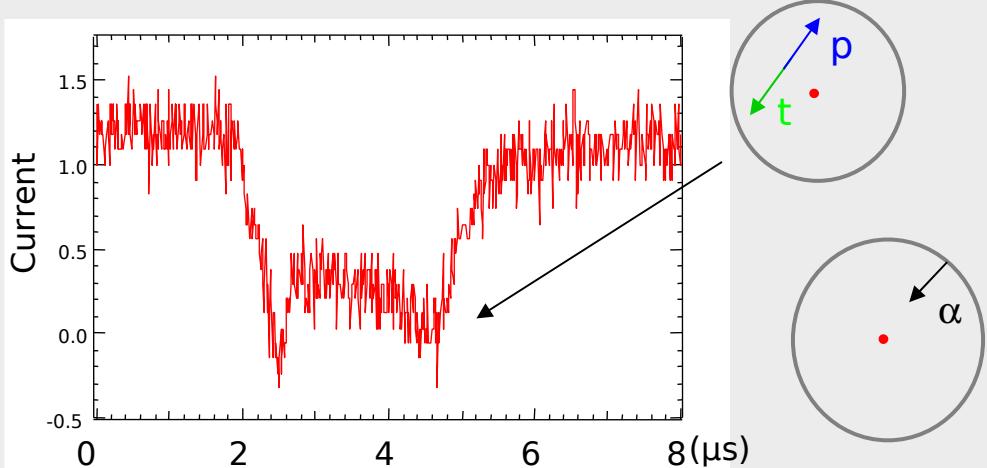


## Oscilloscope:

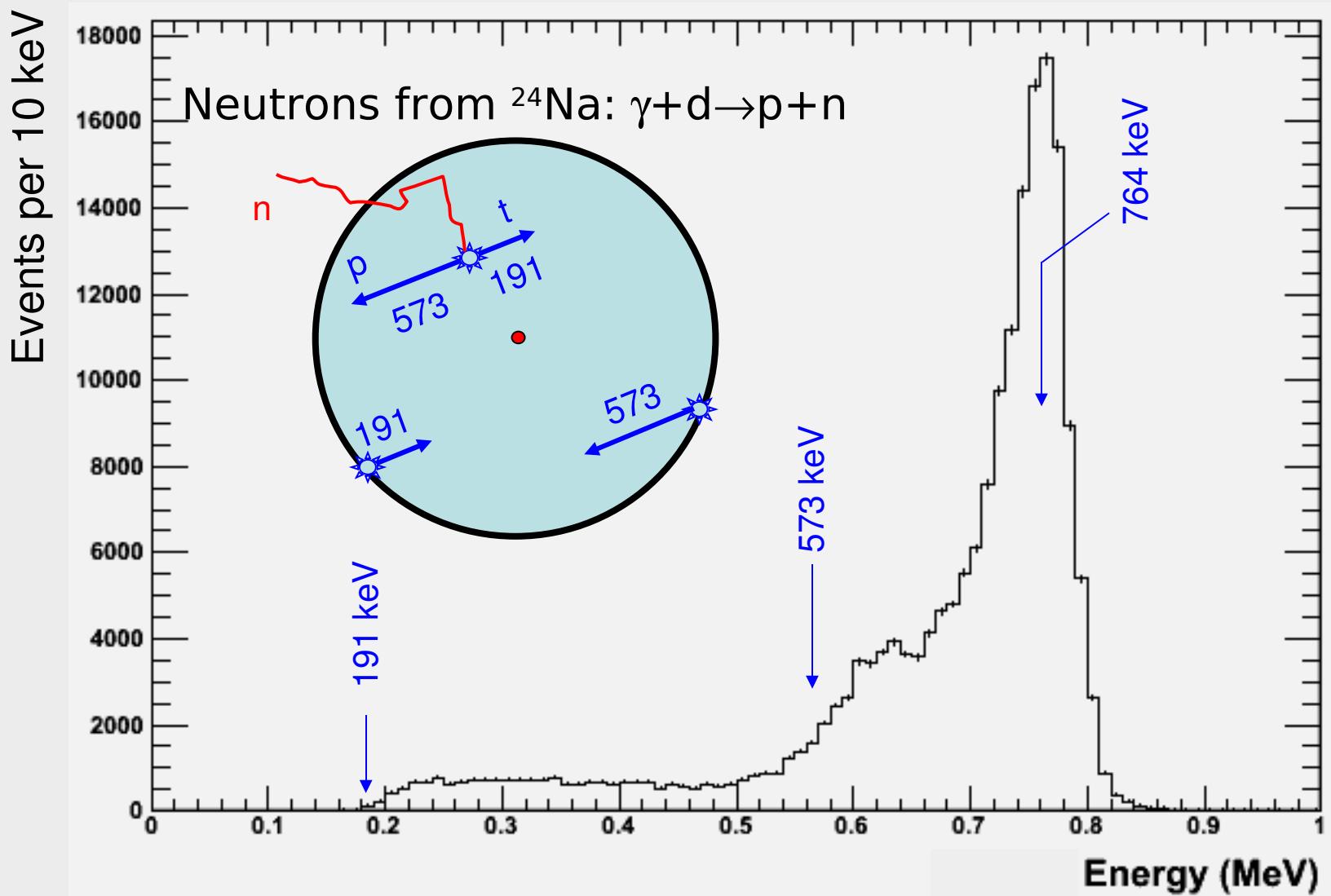
Digitize the pulse, trigger on amplitude, slow readout ( ${}^8\text{B}$ )

## Shaper:

Energy information only, trigger on integral charge, fast readout ( ${}^8\text{B}$ , SN)

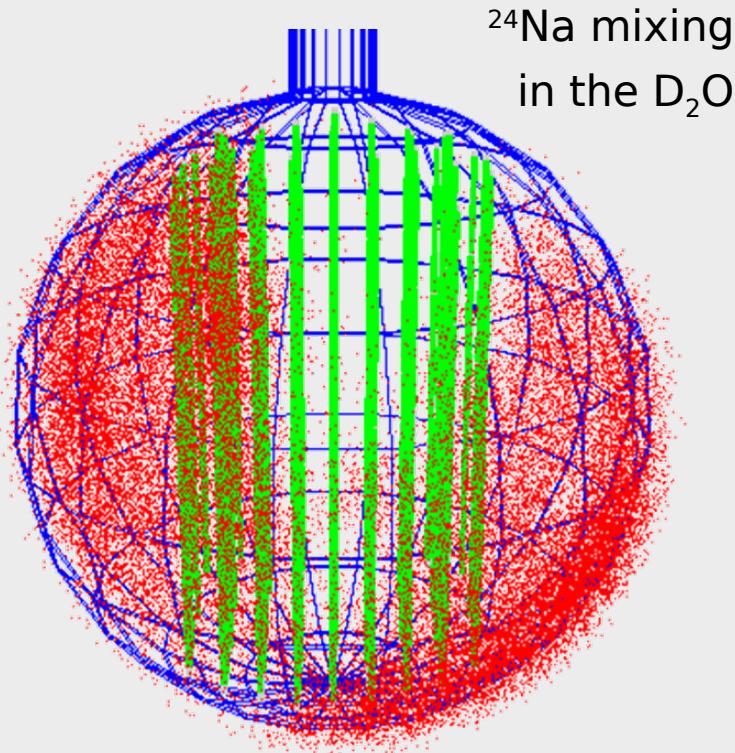
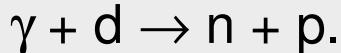


# Energy Spectrum from ${}^3\text{He}(\text{n},\text{p})\text{t}$



# Neutron capture efficiency

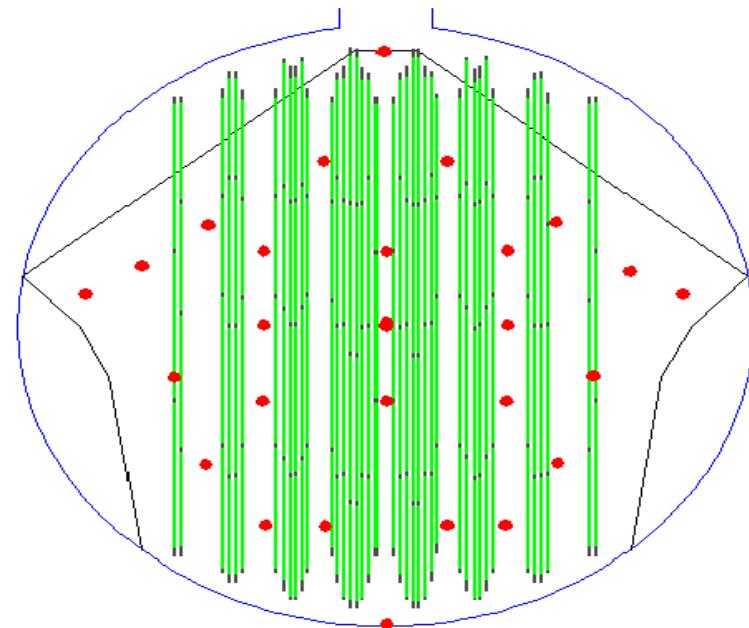
1-  $^{24}\text{Na}$  method: mimic the signal with mixed  $^{24}\text{Na}$  which generates neutrons by:



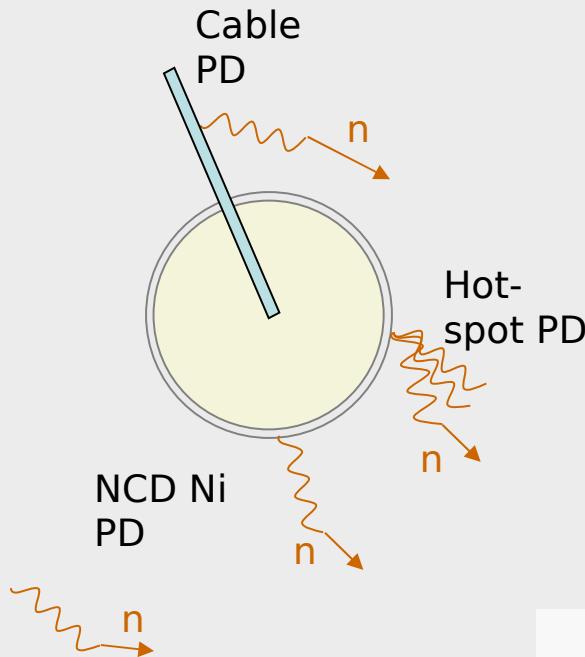
$$\varepsilon_n = 0.211 \pm 0.007$$

2- Monte Carlo method:  
calibrate the Monte Carlo with  
point AmBe and  $^{252}\text{Cf}$  sources.

- Source run locations

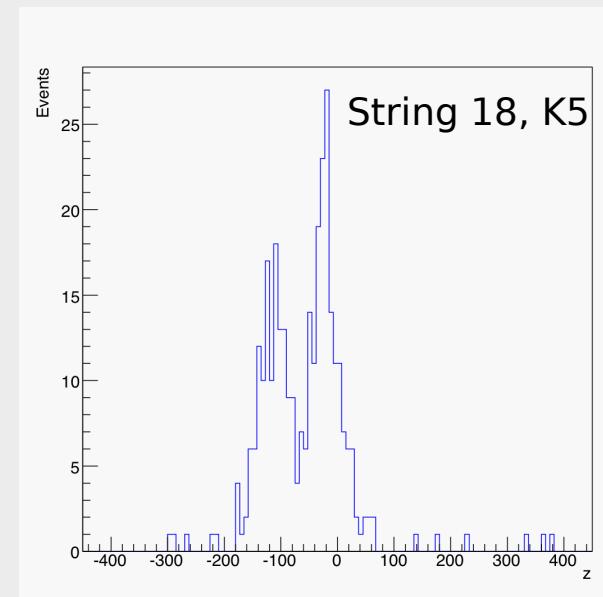
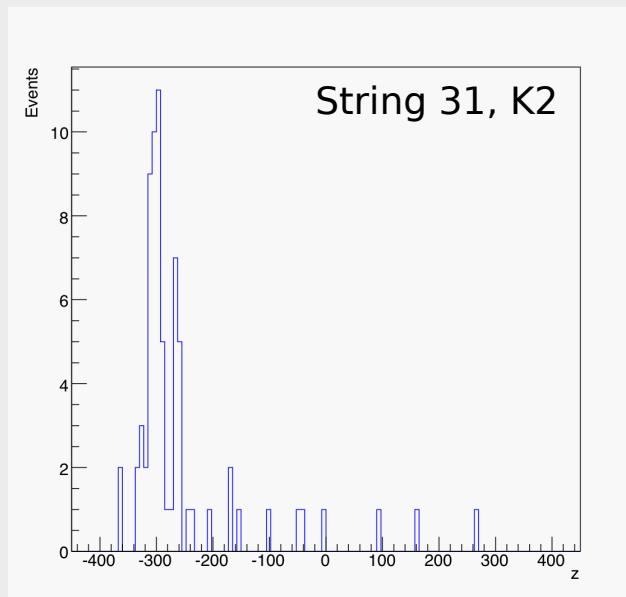


# Neutron background



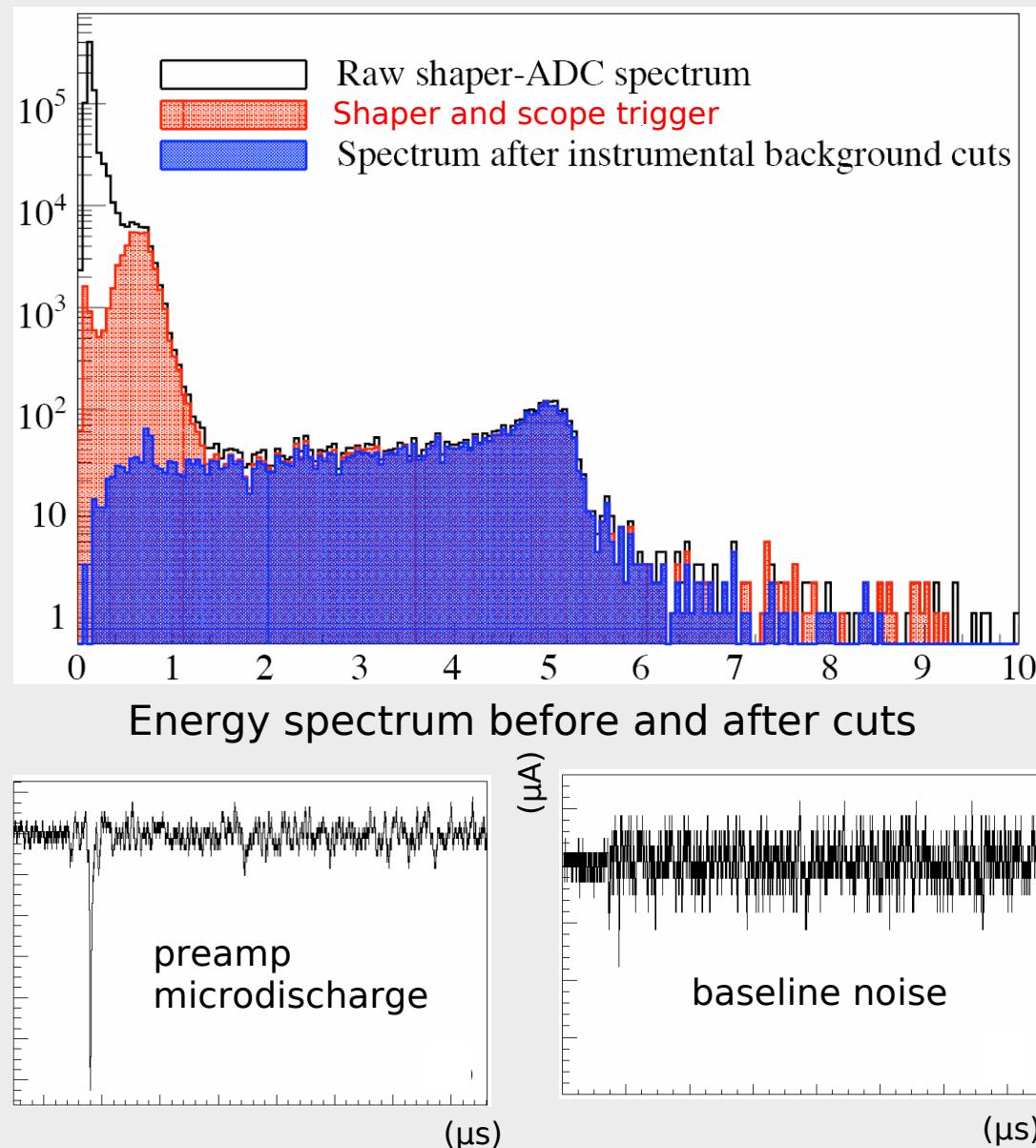
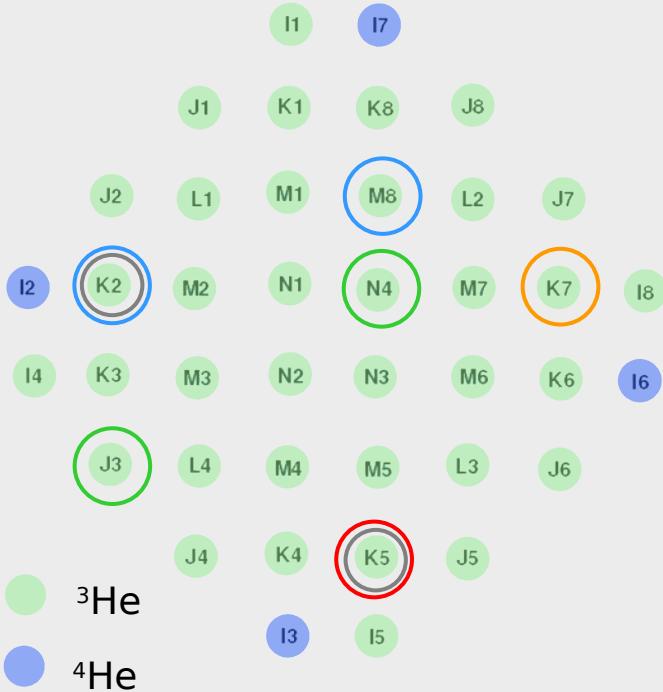
(PD = photodisintegration)

Source	PMT Events	NCD Events
D <sub>2</sub> O photodisintegration	$7.6 \pm 1.2$	$28.7 \pm 4.7$
NCD bulk/ <sup>17</sup> O, <sup>18</sup> O	$4.6^{+2.1}_{-1.6}$	$27.6^{+12.9}_{-10.3}$
Atmospheric $\nu$ / <sup>16</sup> N	$24.7 \pm 4.6$	$13.6 \pm 2.7$
Other backgrounds †	$0.7 \pm 0.1$	$2.3 \pm 0.3$
NCD “hotspots”	$17.7 \pm 1.8$	$64.4 \pm 6.4$
NCD cables	$1.1 \pm 1.0$	$8.0 \pm 5.2$
Total internal neutron background	$56.4^{+5.6}_{-5.4}$	$144.6^{+13.8}_{-14.8}$
External-source neutrons	$20.6 \pm 10.4$	$40.9 \pm 20.6$



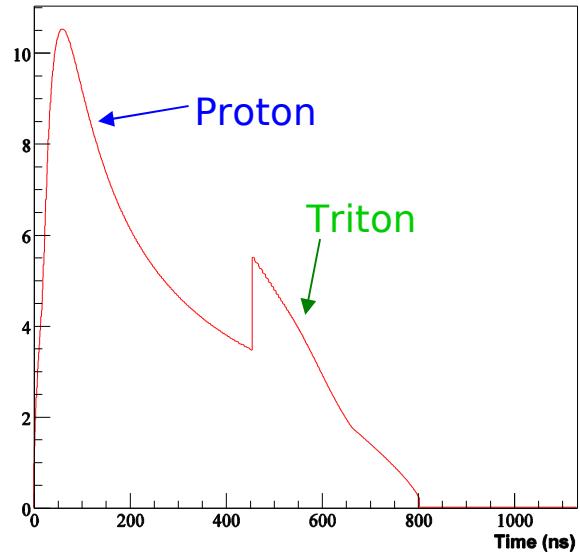
# Instrumental background

- Hot spot
- Gas leak into counter inter-space
- Electrical disconnect
- Electrical micro-discharge
- Gain instability

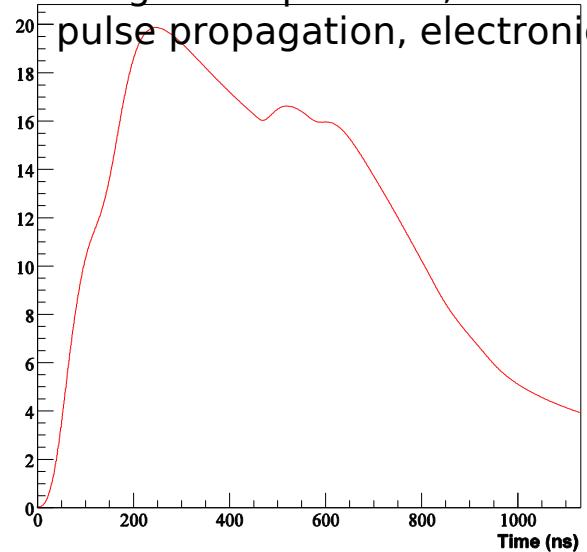


# NCD pulse simulation

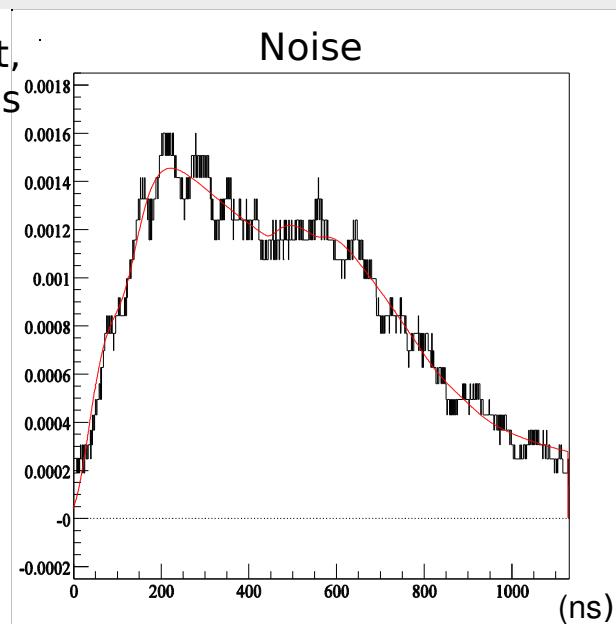
Energy deposition, electron drift



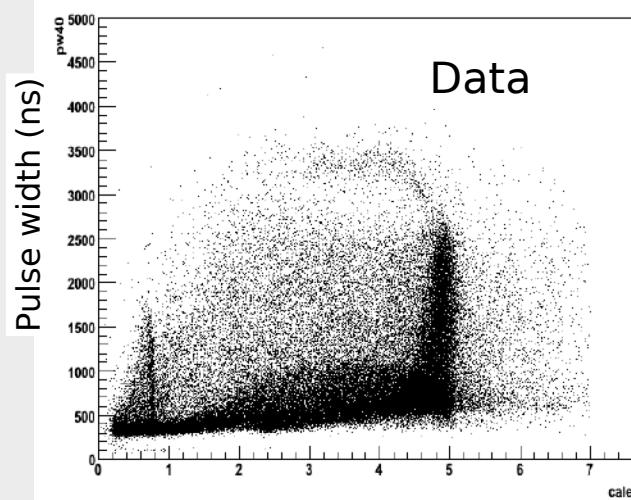
Charge multiplication, ion drift,  
pulse propagation, electronics



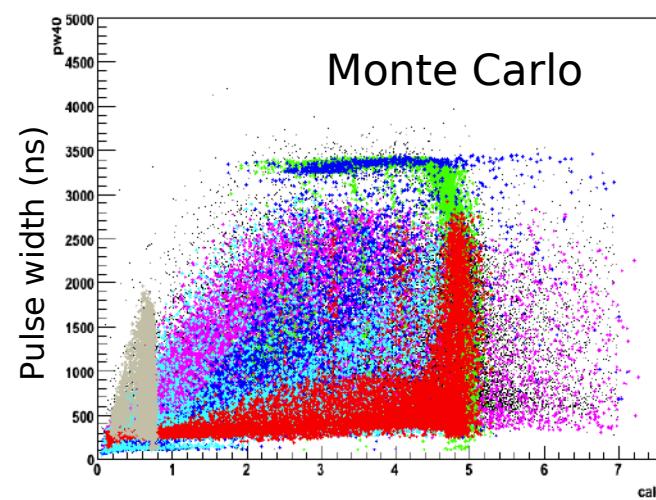
Noise



pw40:cale {cale<7.}



pw40:cale {cale<7.}



**neutrons  
alphas background:**

- wall Po alphas
- wire Po alphas
- wire U/Th alphas
- endcap Po alphas
- wall U/Th alphas

# Blindness scheme and observables

First month of neutrino data open

- 1- Subtract an unknown fraction of neutrino candidates
- 2- Add an unknown amount of muon follower neutrons

Log-likelihood fit  $L = L_{PMT} + L_{NCD}$ :

$$L_{PMT} = - \sum_{d=1}^{N_d} \log \left( \sum_{s=1}^{N_s} n_s f_s(\bar{x}_d) \right) + \sum_{s=1}^{N_s} n_s - \frac{1}{2} \sum_{p=1}^{N_p} \left( \frac{\lambda_p - \bar{\lambda}_p}{\sigma_p} \right)^2$$

$$L_{NCD} = - \sum_{d=1}^{N'_d} \log \left( \sum_{s=1}^{N'_s} n'_s f'_s(\bar{x}_d) \right) + \sum_{s=1}^{N'_s} n'_s - \frac{1}{2} \sum_{p=1}^{N'_p} \left( \frac{\lambda'_p - \bar{\lambda}'_p}{\sigma'_p} \right)^2$$

Signal:

$$f(T, \cos\theta_{\text{sun}}, \rho)$$

$$f(E_{\text{ADC}})$$

Background:

$$f(T) \times f(\cos\theta_{\text{sun}}) \times f(\rho)$$

$$f(E_{\text{ADC}})$$

## Box Opened May 2, 2008:

~10% difference in NC flux uncertainties between the 3 signal extraction codes: after correction of the input energy resolution systematic constraint the errors agree, no effect on the central fit values.

- Parametrization failure of the algorithm (for one extraction code) used to fit the peak value from each ES bin 's distribution: more robust fit method implemented, ES fluxes agree.

# Markov Chain Monte Carlo

The physics parameters (“fluxes”) are fitted allowing nuisance parameters (calibration constants, etc.) to vary weighted by their external uncertainties. The likelihood is maximized via randomized search steps.

## Algorithm:

Initial step i

parameter guesses  $p_i$   
calculate likelihood  $L_i$

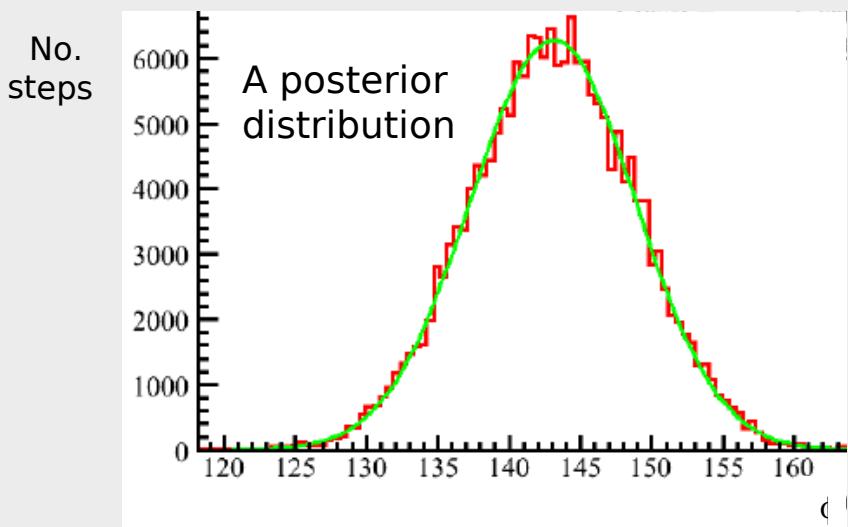
Add random amounts to all parameters

$p_{i+1} = p_i + \text{Norm}(0, \sigma_i)$   
calculate likelihood  $L_{i+1}$

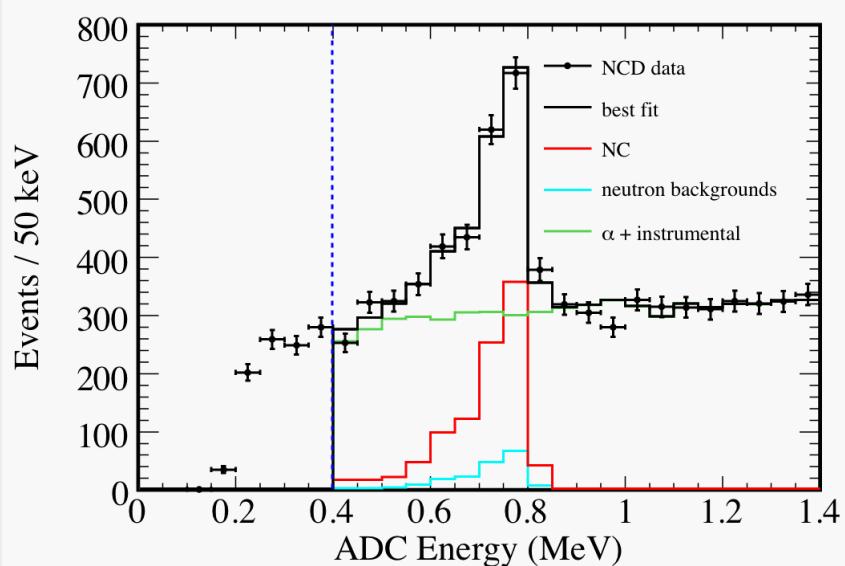
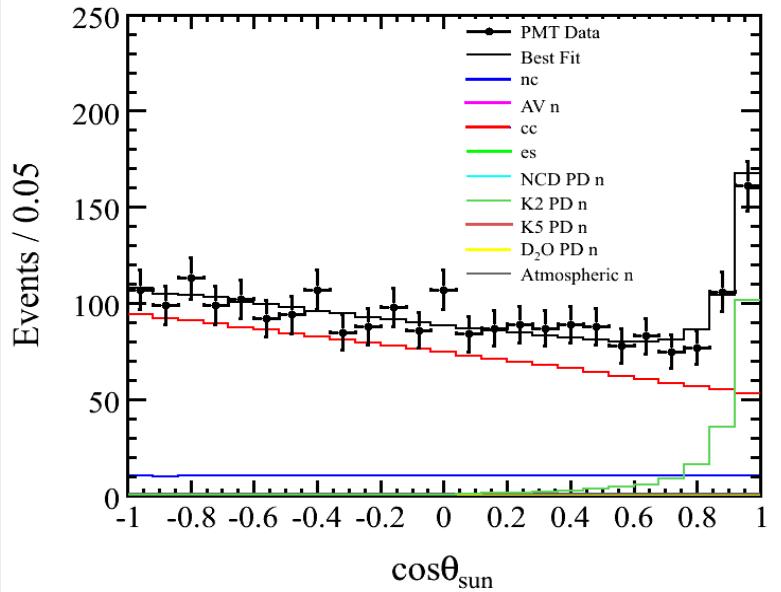
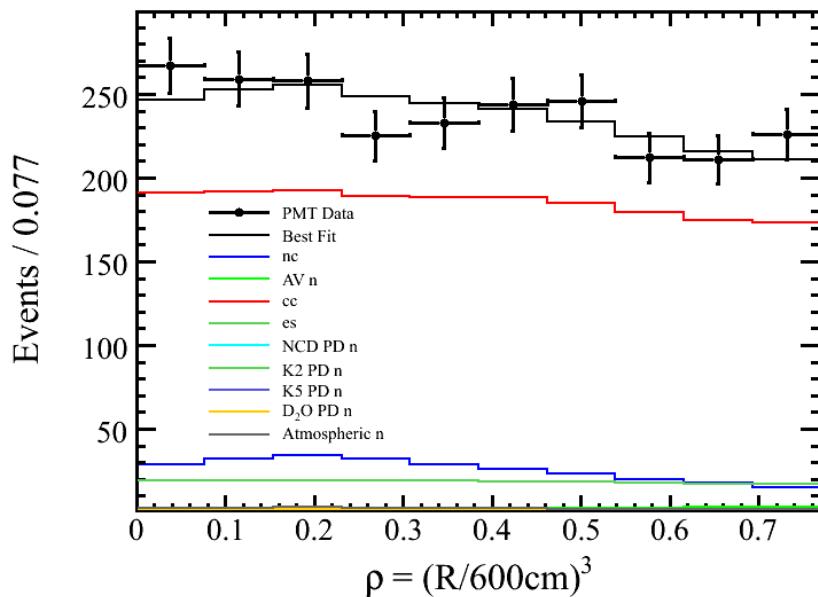
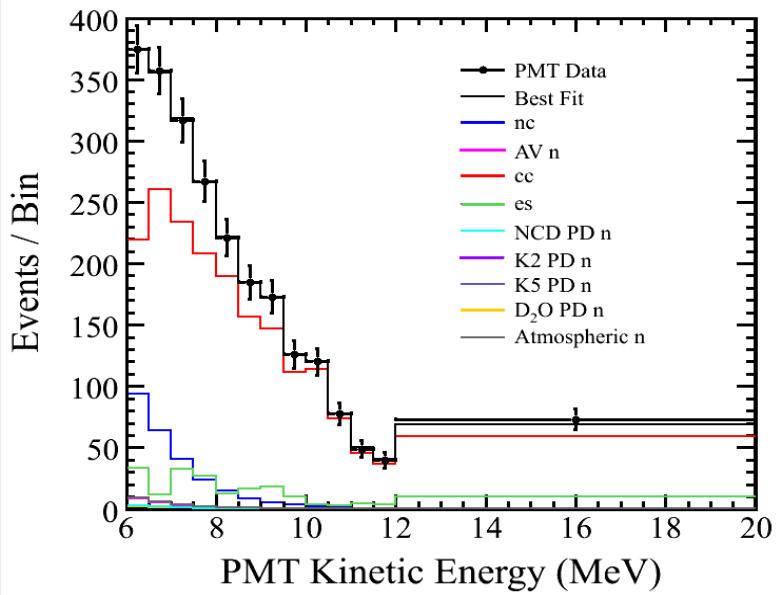
Keep  $p_i$  or  $p_{i+1}$ :

$p_{\text{keep}} = \max(1, L_{i+1} / L_i)$

- 62-parameter likelihood function
  - 13 CC flux energy bins
  - 13 ES flux energy bins
  - NC flux
  - 35 systematic parameters



# Results



# Fluxes and number of events

Fluxes (in unit of  $10^6 \text{ cm}^{-2} \text{ s}^{-1}$ ):

CC  $1.67^{+0.05}_{-0.04}$  (stat)  $^{+0.07}_{-0.08}$  (sys)

ES  $1.77^{+0.24}_{-0.21}$  (stat)  $^{+0.09}_{-0.10}$  (sys)

NC  $5.54^{+0.33}_{-0.31}$  (stat)  $^{+0.36}_{-0.34}$  (sys)

PMT events:

CC  $1867^{+91}_{-101}$

ES  $171^{+24}_{-22}$

NC  $267^{+24}_{-22}$

Background  $77^{+12}_{-10}$

Correlation Matrix for the Salt phase:

	CC	ES	NC
CC	1.00		
ES	-0.16	1.00	
NC	-0.52	-0.06	1.00

Correlation matrix for the NCD phase:

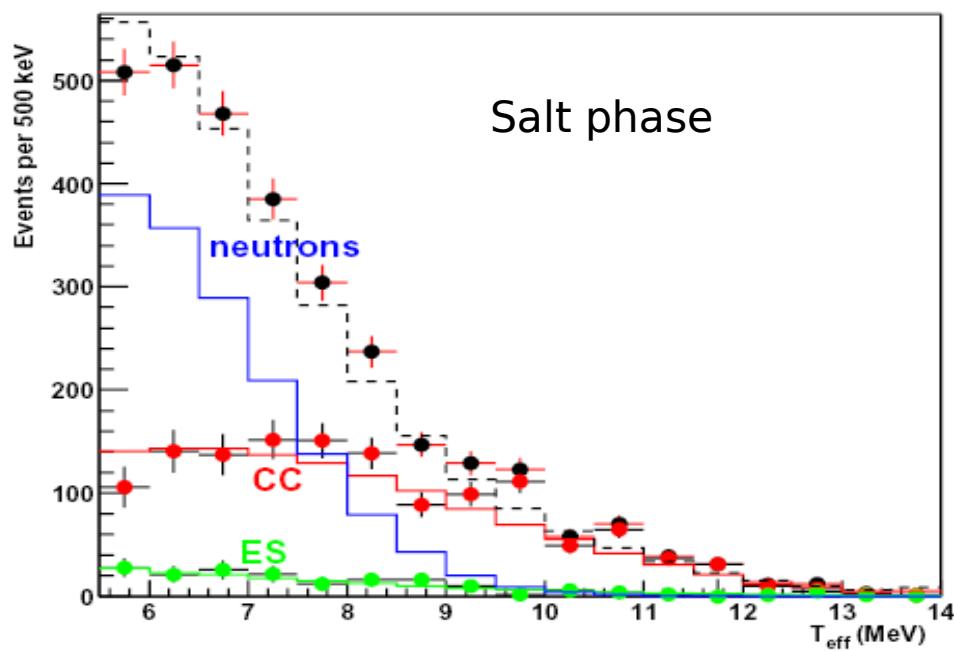
	CC	ES	NC
CC	1.00		
ES	0.24	1.00	
NC	-0.19	0.02	1.00

NCD events:

NC  $983^{+77}_{-76}$

Background  $185^{+25}_{-22}$

# Salt and NCD phases comparison

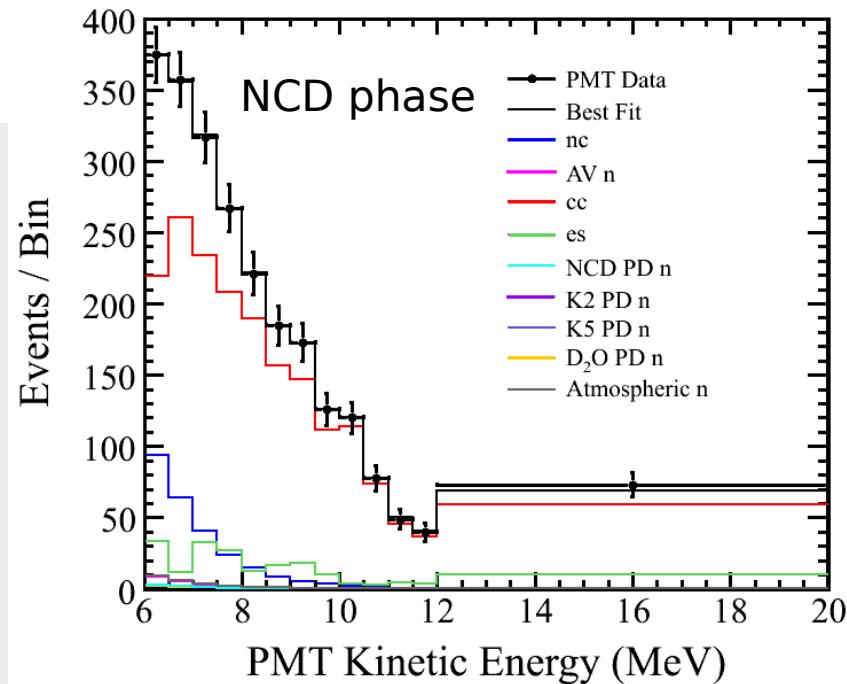


Salt phase

Better measurement of the CC flux.

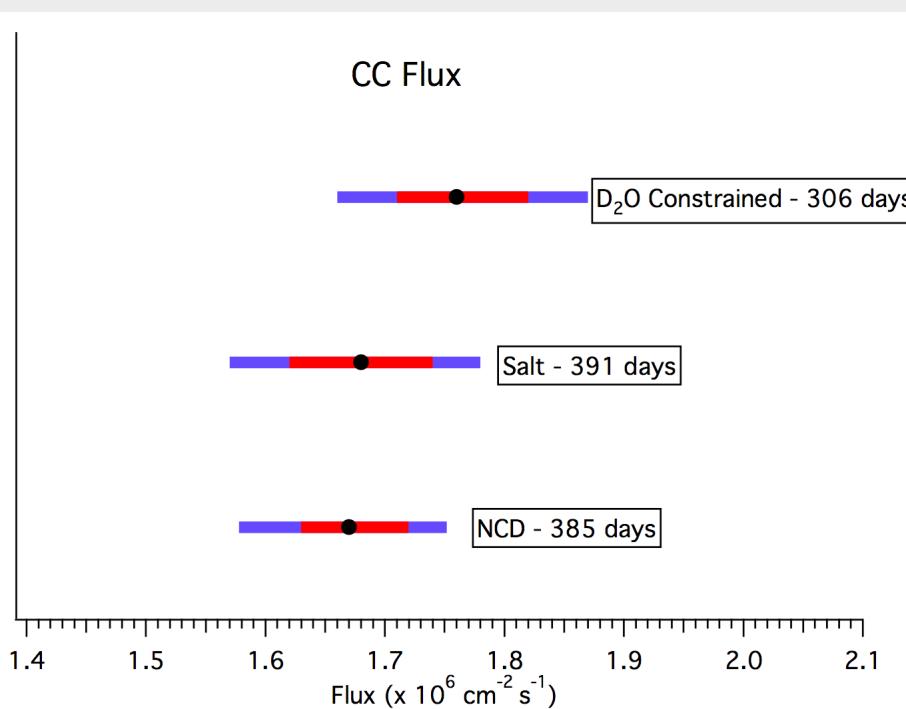
Lower ES flux.

ES results deviation from prior results due to a statistical fluctuation.



# Comparisons

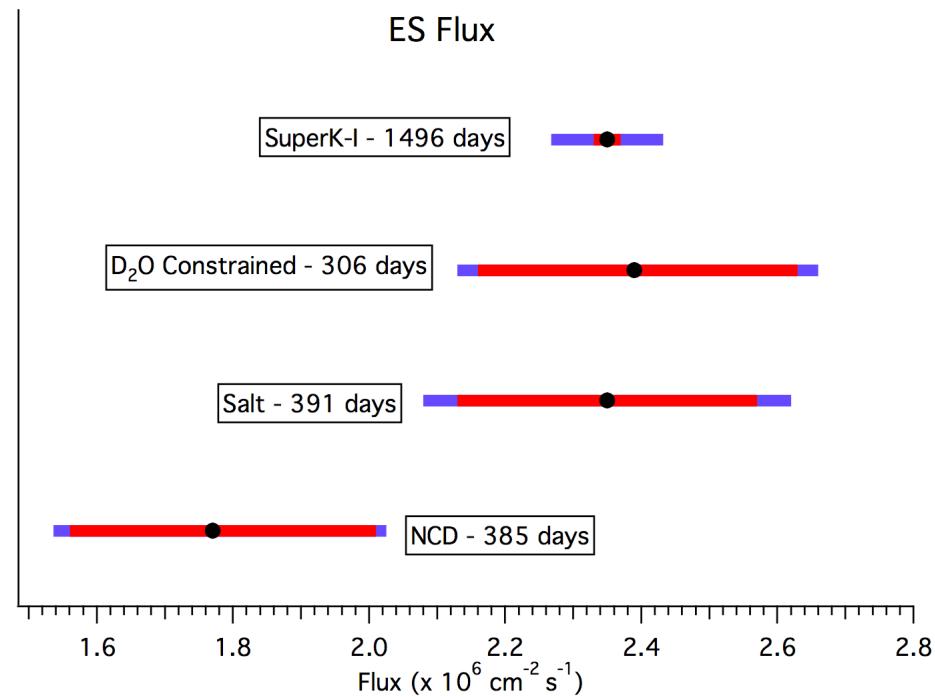
CC Flux



— stat. + syst.

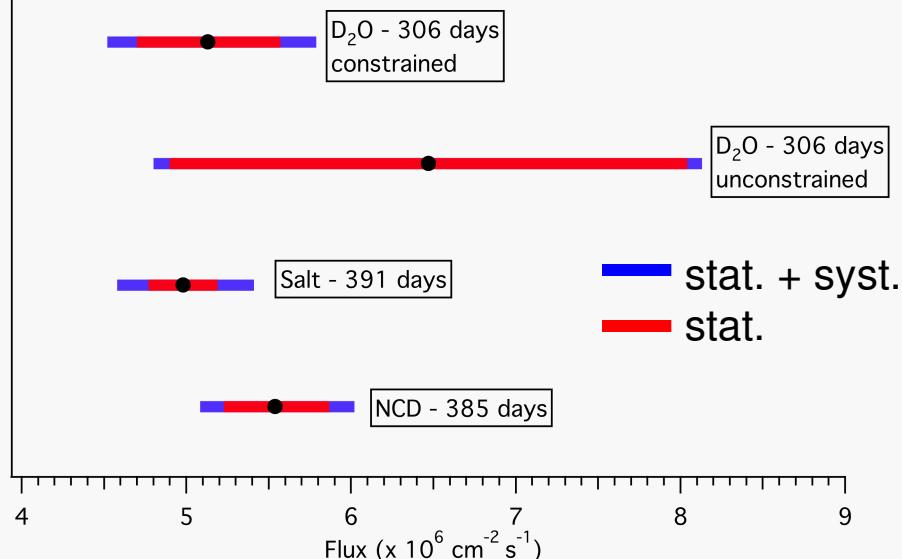
— stat.

ES Flux



# Comparisons

NC flux (corrected to  ${}^8\text{B}$  spectrum of Winter *et al.*)



Agreement with previous measurements (estimated p-value = 0.328)

Agreement with standard solar models

Fluxes (in unit of  $10^4 \text{ cm}^{-2} \text{ s}^{-1}$ )

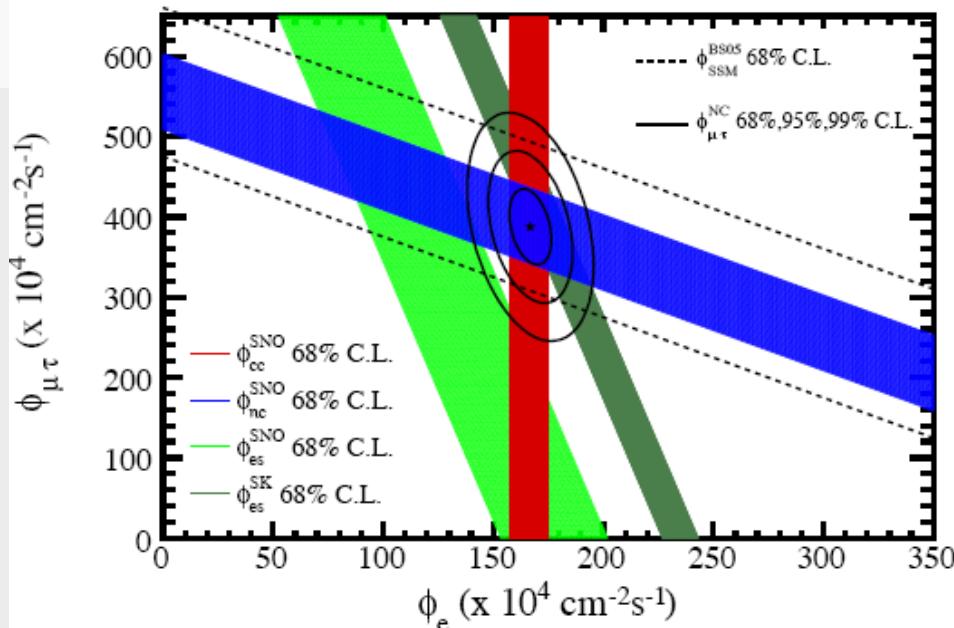
CC: 167(9)

ES: 177(26)

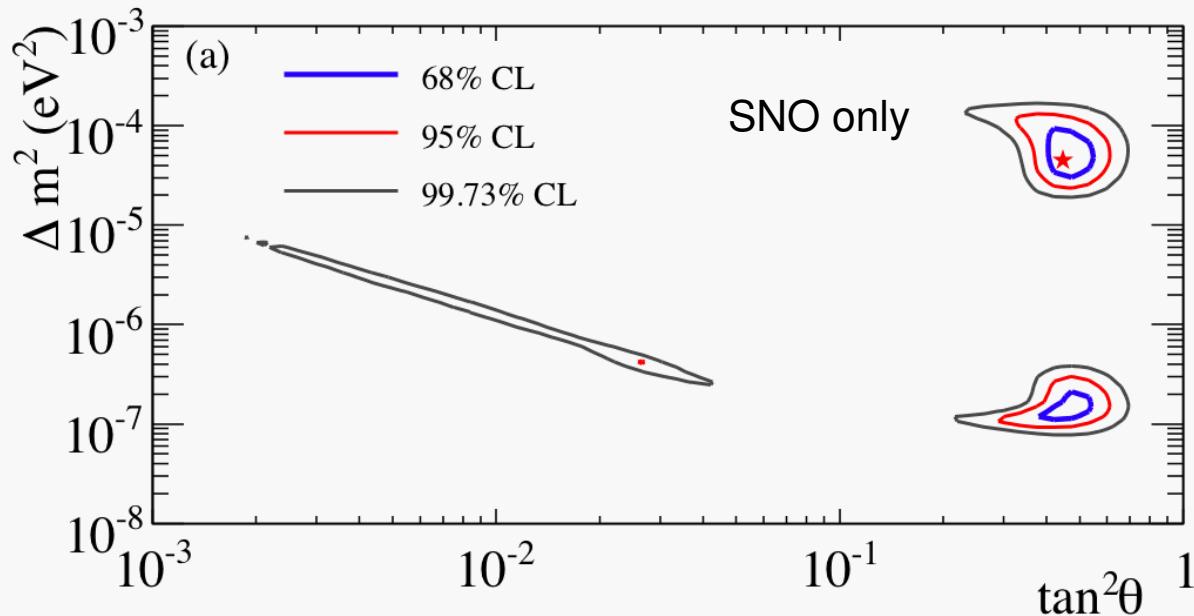
NC: 554(49)

SSM: 569(91) [BSB05-OP: Ap. J. 621, L85, 2005]

Super-K: 235(8) [PRD 73, 112001, 2006]



# 2-neutrinos oscillation contours



a) SNO only:  
 $D_2O$  & Salt day and night spectra, NCD phase fluxes

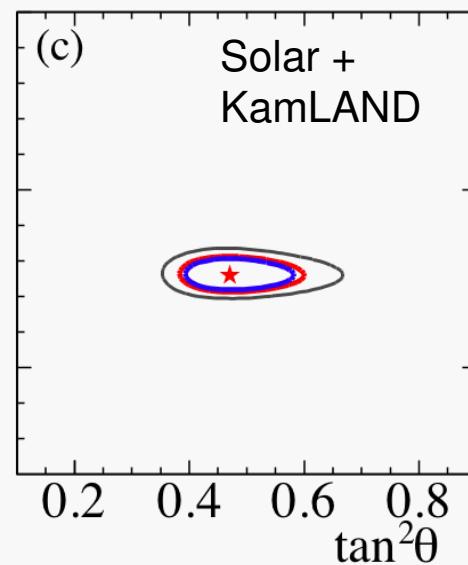
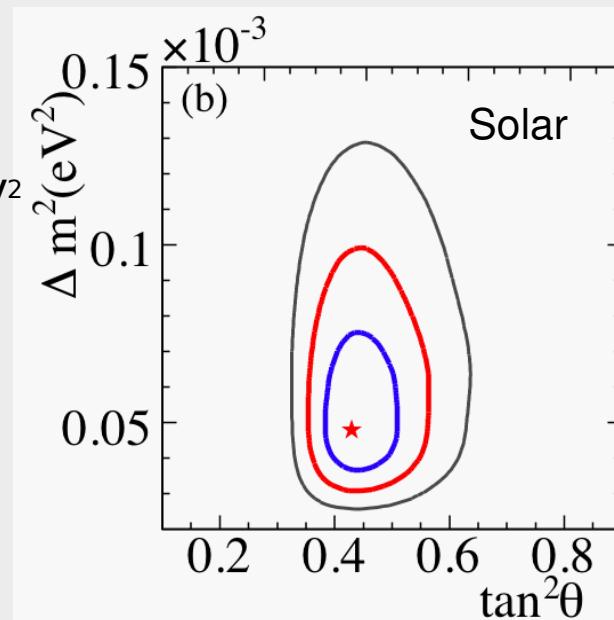
- b) Solar Global:  
 SNO, Super-K, Cl, Ga, Borexino  
 c) Solar Global + KamLAND

Solar+KamLAND best fit:

$$\Delta m_{12}^2 = 7.59^{+0.19}_{-0.21} \times 10^{-5} \text{ eV}^2$$

$$\theta_{12} = 34.4^{+1.3}_{-1.2} \text{ degrees}$$

$$\tan^2 \theta_{12} = 0.468^{+0.048}_{-0.040}$$



# Conclusion

## **Results from the NCD phase:**

Independent measurement of the  ${}^8\text{B}$  flux.

NCD results agree well with previous SNO phases.

Reduced correlations between CC and NC.

Different systematics.

New precision on  $\theta_{12}$ , 40% improvement on our previous result. [Phys. Rev. Letter 101 11301 (2008)]

## **More from SNO:**

LETA (Low Energy Threshold Analysis)

Three phase analysis

Three neutrino analysis

*hep* flux

Day-night, other variations

Muons, atmospheric  $\nu$  [accepted by PRD]

# The SNO Collaboration

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NERSC PDSF

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STFC (formerly Particle Physics and Astronomy Research Council)

## Portugal:

FCT

# Backup Slides

# The big picture

The Maki-Nakagawa-Sakata-Pontecorvo (MNSP or PMNS or MNS) matrix:

$$\begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}$$

Equation of evolution:

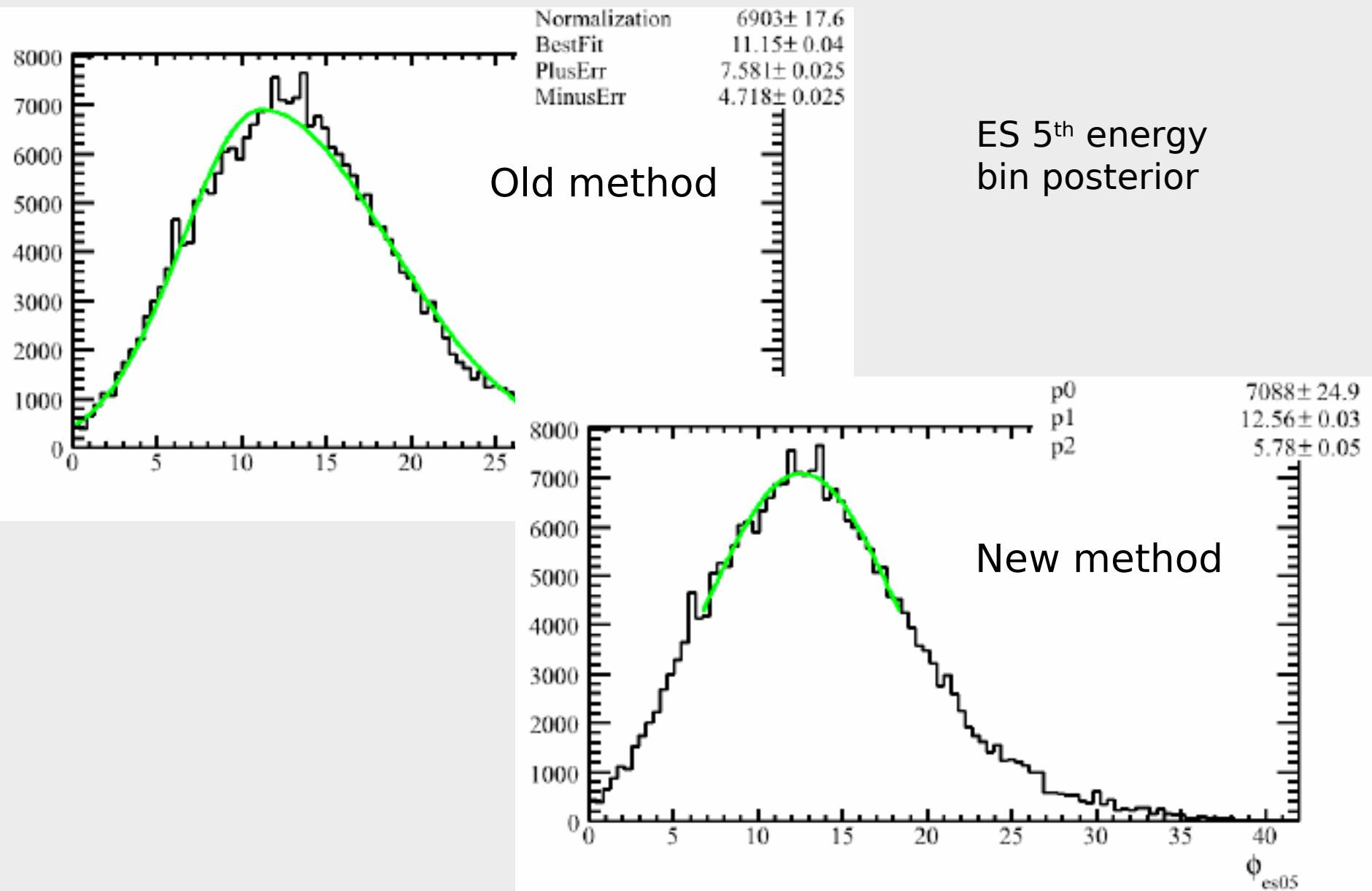
$$|v_\alpha(L)\rangle = \sum U^*_{\alpha i} \exp(-i m_i^2 L/2E) |v_i(L=0)\rangle$$

3 mixing angles  
1 CP violation phase  
2 Majorana phases

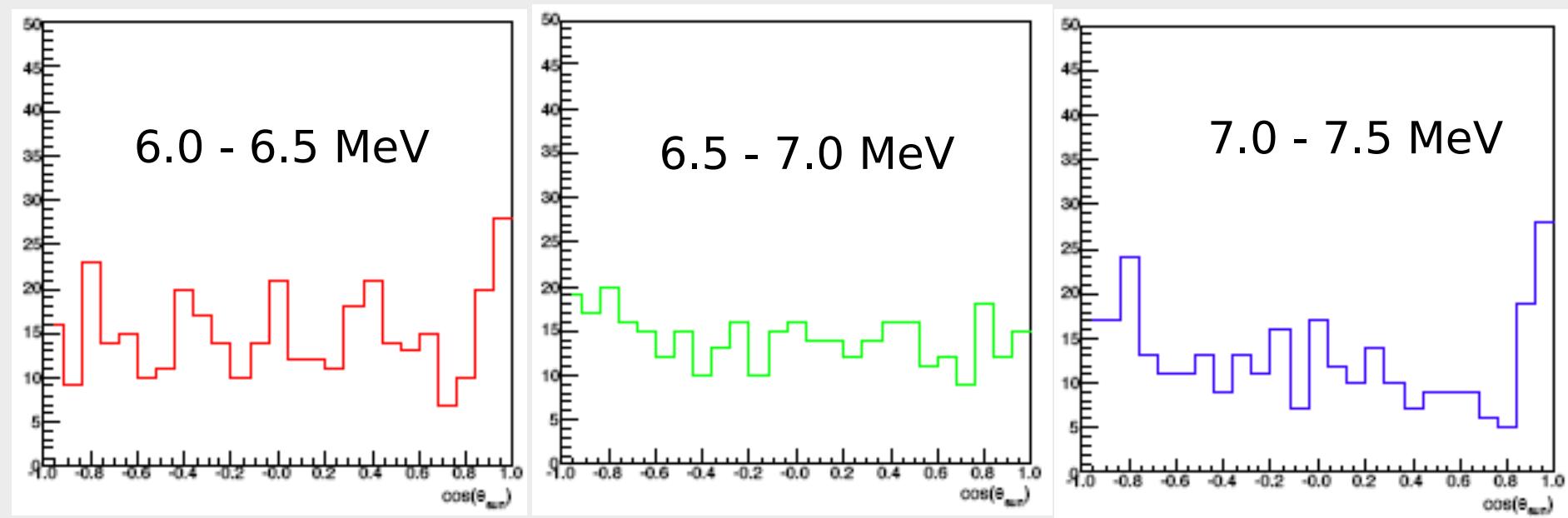
Oscillation probability (vacuum case):

$$P(v_\alpha \rightarrow v_\beta) = | \langle v_\alpha | v_\beta \rangle |^2 = \delta_{\alpha\beta} - 4 \sum U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \sin^2(\Delta m_{ij}^2 L / 4E)$$

# Change in parameterization for ES fit



# Angular distributions for ES



Distribution for the energy bin 6.5-7.0 MeV: no peak at  $\cos(\theta_{\text{sun}}) = 1$  as expected.

Statistical fluctuation (1.3% probable to obtain such a low number in this bin assessed by a MC of 10000 trials).

# $\chi^2$ map (SNO collaboration)

